

Skywatching: Seeing and Understanding Cosmic Wonders

Course Guidebook

Professor Alex Filippenko
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PUBLISHED BY:

THE GREAT COURSES

Corporate Headquarters

4840 Westfields Boulevard, Suite 500

Chantilly, Virginia 20151-2299

Phone: 1-800-832-2412

Fax: 703-378-3819

www.thegreatcourses.com

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Professor Alex Filippenko received his bachelor's degree in Physics from the University of California, Santa Barbara, and his doctorate in Astronomy from the California Institute of Technology. After a 2-year postdoctoral fellowship at the University of California, Berkeley, he joined the faculty at UC Berkeley, where he has remained through the present. A member of the International Astronomical Union, Dr. Filippenko has served as president of the Astronomical Society of the Pacific and as councilor of the American Astronomical Society. He was elected to the California Academy of Sciences in 1999 and to the National Academy of Sciences in 2009.

Dr. Filippenko is an observational astronomer who makes frequent use of the Hubble Space Telescope and the Keck 10-meter telescopes, and his primary areas of research are exploding stars (supernovae), active galaxies, black holes, gamma-ray bursts, and cosmology. He and his collaborators recognized a new class of exploding star, obtained some of the best evidence for the existence of small black holes in the Milky Way Galaxy, and found that other galaxies commonly show vigorous activity in their centers that suggests the presence of supermassive black holes. His robotic telescope at Lick Observatory in California was, during the years 1998–2009, the world's most successful search engine for nearby exploding stars, discovering more than 800 of them; today, it continues to scan the skies for supernovae. He also made major contributions to the discovery that the expansion rate of the Universe is speeding up with time (the accelerating Universe), propelled by some kind of mysterious dark energy. This was the top “Science Breakthrough of 1998” according to the editors of *Science* magazine, earning him a share of the 2007 Gruber Cosmology Prize, work that went on to receive the 2011 Nobel Prize in Physics.

Dr. Filippenko's research findings are documented in about 700 published papers and in more than 1400 abstracts and astronomical telegrams. One of the world's most cited astronomers, he has been recognized with several major awards, including the Newton Lacy Pierce Prize of the American Astronomical Society (1992), the Robert M. Petrie Prize of the Canadian Astronomical Society (1997), and the Richtmyer Memorial Award of the American Association of Physics Teachers (2007). Dr. Filippenko has also been a Guggenheim Foundation Fellow (2001) and a Phi Beta Kappa Visiting Scholar (2002). He has held distinguished visiting positions at numerous colleges and universities, including the Marlar Lecturer at Rice University, the Iben Lecturer at the University of Illinois, the Kaufmanis Lecturer at the University of Minnesota, the Pappalardo Lecturer at the Massachusetts Institute of Technology, the Bunyan Lecturer at Stanford University, the Salpeter Lecturer at Cornell University, and both the Spitzer Lecturer and Farnum Lecturer at Princeton University.

At the UC Berkeley campus, Dr. Filippenko has won the coveted Distinguished Teaching Award (1991) and the Donald S. Noyce Prize for Excellence in Undergraduate Teaching in the Physical Sciences (1991), each of which is generally given at most once per career. Students have voted him Best Professor on Campus a record 8 times, and his introductory astronomy class has been voted Best Class on Campus several times. He also received the 2002 Distinguished Research Mentoring of Undergraduates Award. At the end of 2006, he was honored as the Doctoral and Research Universities National Professor of the Year by the Carnegie Foundation for the Advancement of Teaching and the Council for Advancement and Support of Education. In 2010, he received the Richard H. Emmons Award of the Astronomical Society of the Pacific for excellence in the teaching of college-level introductory astronomy for non-science majors.

Dr. Filippenko has delivered more than 700 public lectures on astronomy to a wide range of audiences and has played a prominent role in numerous science newscasts and television documentaries, such as *Mysteries of Deep Space*, *Stephen Hawking's Universe*, *Runaway Universe*, *Exploring Time*, and about 40 episodes spanning 6 seasons of *The Universe* on The History Channel. With Jay M. Pasachoff, he coauthored an introductory astronomy textbook, *The Cosmos: Astronomy in the New Millennium*, now in its third edition; it

won the 2001 Texty Excellence Award of the Text and Academic Authors Association for the best new textbook in the physical sciences. He was also the recipient of the 2004 Carl Sagan Prize for Science Popularization from the Trustees of Wonderfest, the San Francisco Bay Area Festival of Science.

In 1998, Dr. Filippenko produced a 40-lecture introductory astronomy video course with The Great Courses, and in 2003, he recorded a 16-lecture update. These were replaced and extended in 2006 with his 96-lecture *Understanding the Universe: An Introduction to Astronomy, 2nd Edition*—the largest course ever produced by The Great Courses with a single professor. In 2009, he recorded the course *Black Holes Explained*. ■

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Skywatching: Seeing and Understanding Cosmic Wonders

Scope:

This course is about looking at the sky and objects or phenomena in it during the day and night, over small and large distances from Earth. Why should skywatching be limited to the stars when there are so many additional cosmic wonders to see, most without even the aid of a telescope? In these lectures, we will go on a visual tour of rainbows and coronas, solar and lunar halos, sunspots and prominences, constellations and other star patterns, planets and their motions, the Moon and lunar phases, solar and lunar eclipses, and “falling stars.” Additional topics include comets, artificial satellites, cloud formations, the Milky Way, zodiacal light, the blue sky and twilight colors, lightning, and many other phenomena.

Why does the Moon appear red during a total lunar eclipse? What determines the location, duration, and visual appearance of a total solar eclipse, and how does one safely view an eclipse? Why are auroras most dazzling after the occurrence of coronal mass ejections from the Sun? Where do the meteors in meteor showers come from, and how should you best view them? Can we see galaxies millions of light years away? Is the full Moon really largest when it's near the horizon, or is this just an illusion? How can you maximize the chances of seeing the elusive “green flash” when the Sun is setting? Is the Earth's shadow visible shortly thereafter in the opposite direction? What does the darkness of the night sky tell us about the origin of the universe? Each lecture offers insights into some of nature's most mysterious and beautiful offerings, including their underlying explanations and how to see them.

We begin with an overview of the day and night skies over a vast range of distances; as we'll learn, in a single view, we may see objects closer than our horizon, just a few miles away, up through the vast depths of space, more than 10 billion billion miles away. In Lecture 2, we explain why the sky varies in brightness and shades of blue in different directions. Various types of clouds are also described, along with some of their physical characteristics, and the nature of lightning and related electrical phenomena is explored. The interaction of

sunlight with drops of water is the subject of Lecture 3. In addition to explaining various types of rainbows, the lecture also describes related phenomena, such as solar and lunar coronas, iridescent clouds, and glories, with plenty of tips for successful and safe viewing. We then explore the interaction of sunlight with ice crystals high in the atmosphere, which gives rise to various types of halos around the Sun and the Moon, in addition to colorful arcs and isolated bright patches. These are rarely noticed by most people but, in fact, can be more common than rainbows. Lecture 5 concentrates on sunrise and sunset, providing explanations for the familiar orange and red colors of the clouds and of the elusive “green flash,” with suggestions for how to see it. We also point out the Earth’s shadow and the bright Belt of Venus above it.

In Lecture 6, we make a transition to nighttime, first exploring the various stages of twilight. Bright stars and constellations are discussed, with helpful advice on how to find your way around the night sky at different times and seasons. The observed and inferred properties of some of the brightest stars are described. Lecture 7 concentrates on locating various planets of our solar system in the night sky, providing simple explanations of their sometimes complex-looking motions. Venus, the bright morning or evening star, is the easiest to find, but many of the others can readily be seen, as well. The Moon is the subject of Lecture 8, ranging from observable features on its surface, to the explanation of lunar phases and how they correlate with the times the Moon is observable, to the Moon illusion and the eerie colors of total lunar eclipses. We then move on to observations of Earth’s artificial satellites, such as the International Space Station, comets that come in from the Solar System’s deep freeze, and meteors and meteor showers.

We explore the Sun in Lecture 10, learning about various signs of its activity, such as sunspots and prominences, and how to view them safely. Energetic charged particles from solar flares interact with Earth’s magnetic field and atmosphere, producing beautiful, ghostly auroras. Lecture 11 is devoted to total solar eclipses, which rank among nature’s grandest and most thrilling spectacles; seeing one should be on everyone’s must-do list! Finally, in Lecture 12, we see the dark night sky in all its glory, examining objects and phenomena that can only be seen far from city lights, in moonless skies. The magnificent Milky Way, in particular, is an awe-inspiring view of our own galaxy. ■

Day and Night Skies across All Distances

Lecture 1

This course, *Skywatching: Seeing and Understanding Cosmic Wonders*, represents a union of astronomy and atmospheric science. As we'll see throughout the course, we can explore many interesting objects in the sky with our unaided eyes or a pair of binoculars, and our observations can be greatly enhanced by a physical understanding of the scientific phenomena that we are witnessing. In this first lecture, we'll take a tour of the sky, from the nearby objects in Earth's troposphere out to the farthest things we can see in our Universe.

Vast Distances and Incredible Phenomena

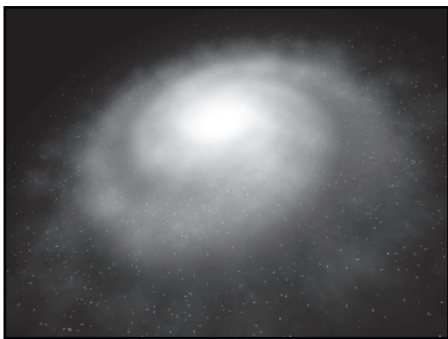
- Skywatching encompasses the sky at a range of distances that is astonishing to contemplate.
- On a clear, dark, moonless night, the **Andromeda galaxy** can be seen with the naked eye.
- Viewing and learning about the sky allow us to appreciate the beauty of a comet, a meteor, and the phenomenon of twilight with greater understanding.

The Celestial Sphere, the Zenith, and the Horizon

- When we look up at the night sky, the stars appear to be plastered on a dome, similar to what you see in a planetarium. This dome is called the **celestial sphere**, and it rotates around us as Earth slowly spins on its axis.
- The **zenith** is defined to be the point in the sky straight above you, and the **horizon** is where the celestial sphere appears to touch the ground. It naturally divides the celestial sphere into two equal halves, above and below. More precisely, the horizon is defined by

the line tangent to Earth in the direction you're looking, the line that just barely touches Earth.

- How far away the horizon appears depends on your height. The distance to the horizon in miles is about 1.2 times the square root of your height in feet.
- To most people, the celestial sphere appears flattened. The zenith seems much closer to us than the horizon, even though it isn't. Try to remember that the apparently flattened dome is just an illusion. Not all objects in the sky are close if overhead and distant if near the horizon.



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The Andromeda galaxy, sketched here, is about 15 billion billion miles away.

A Tour of the Sky

- The blue color of the sky is caused by sunlight reflecting off of air molecules. Most of the air is very nearby, within a few miles. Almost all of the **atmosphere**, in fact, is within a height of about 60 miles of Earth, and three-quarters of the mass of the atmosphere is within only 6 miles of sea level.
- The **troposphere** is the region of the atmosphere from Earth's surface to about 8 miles above. The **stratosphere** is the region from about 8 to 30 miles above the surface. The **ozone layer**, which protects us from the Sun's **ultraviolet** radiation, is near the top of the stratosphere.
- Next is the **mesosphere**, up to about 60 miles, and beyond that is the **ionosphere**, which is partly ionized and permeated by Earth's magnetic field.

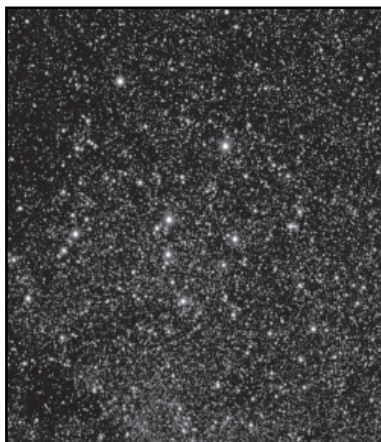
- Familiar objects, such as clouds, airplanes, rainbows, and solar halos, are all in the razor-thin troposphere that hugs Earth. Shooting stars generally occur in the mesosphere; the northern lights are in the ionosphere; and artificial satellites are in the upper ionosphere and the lower magnetosphere.
- The **Moon** is another familiar object in the sky; it's about 240,000 miles away from Earth. The **Sun** is about 93 million miles away, or about 24,000 Earth radii. This distance is known as the **astronomical unit (AU)**.
- The Sun is about 390 times larger than the Moon and 390 times farther away from us than the Moon is. This amazing coincidence of relative sizes and distances can result in a total solar eclipse. It's important never to look at the Sun for more than a split second except when it is fully eclipsed, or within a few seconds of the total eclipse. To view the Sun safely under most conditions, use a piece of shade 14 welder's glass or look online for a pair of glasses that cuts out 99.999% of all incoming rays.

Nearby Planets in Our Solar System

- To the unaided eye, **planets** look like stars. The planets move along with time, and if you're familiar with the night sky, especially the zodiacal constellations through which the planets wander, you can often tell if a particular star looks out of place. When you see an extra-bright star that doesn't belong, it may be a planet.
- Though the planets look point-like to the naked eye, spacecraft offer close-up views and show amazing details of these alien worlds. An image of Jupiter from the *Voyager* spacecraft shows that it's a gigantic planet with a tumultuous atmosphere.
- Similarly, images of Saturn's rings show that they consist of small bits of rubble, mostly ice; these probably came from a tidally disrupted moon or a moon that never fully formed.

The Realm of the Stars

- The stars that we see as tiny pinpoints of light are very distant suns, typically about the same size as our own Sun. They look so small and faint because they're incredibly far away from us.
- The closest star, Alpha Centauri, is about 270,000 AU (25 trillion miles) away.
- Sirius, which can be found to the lower left of the great hunter Orion's belt, is the brightest star in the sky. It's about twice as distant as Alpha Centauri. Betelgeuse, in the left shoulder of Orion as seen by us, is about 150 times farther away than Alpha Centauri.
- Most of the brightest stars in the sky are not nearby, and most of the closest stars do not appear to be very bright. The **apparent brightness** of a star is directly proportional to its **luminosity** and inversely proportional to the square of its distance from us (the inverse-square law of light).
- The **inverse-square law** arises because a given amount of light emitted by an object per second spreads out over ever-larger spheres. The same amount of light passes through a progressively larger surface area, so each unit of surface area must receive a progressively smaller fraction of the total light.
- To appear bright, a star must have either a very high luminosity or a small distance or both. The closest stars to us tend to have low luminosity.



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A star's brightness is not a measure of its closeness to or distance from Earth. Most of the brightest stars are quite far from us.

- Betelgeuse is one example of an extremely powerful, luminous star. It is a massive star that will actually blow up as a supernova sometime in the next half million years.
- The vast distances that we talk about with stars are given in terms of light years. A light year is about 6 trillion miles, or 10 trillion kilometers.
- When we look at stars that are hundreds or even thousands of light years away, we are looking hundreds or thousands of years into the past. We even see the Sun as it was in the past—about 8.3 minutes ago.
- Polaris, the famous North Star, is about 430 light years away, while Betelgeuse is about 640 light years away. It is challenging, however, for astronomers to determine accurate distances to stars.
- V762 in the constellation Cassiopeia is the most distant star in the Milky Way galaxy that may be visible to the naked eye on a clear, dark, moonless night. It's about 16,000 light years away.
- Exploding stars are so powerful that they can sometimes be seen with the naked eye at distances of more than 100,000 light years.

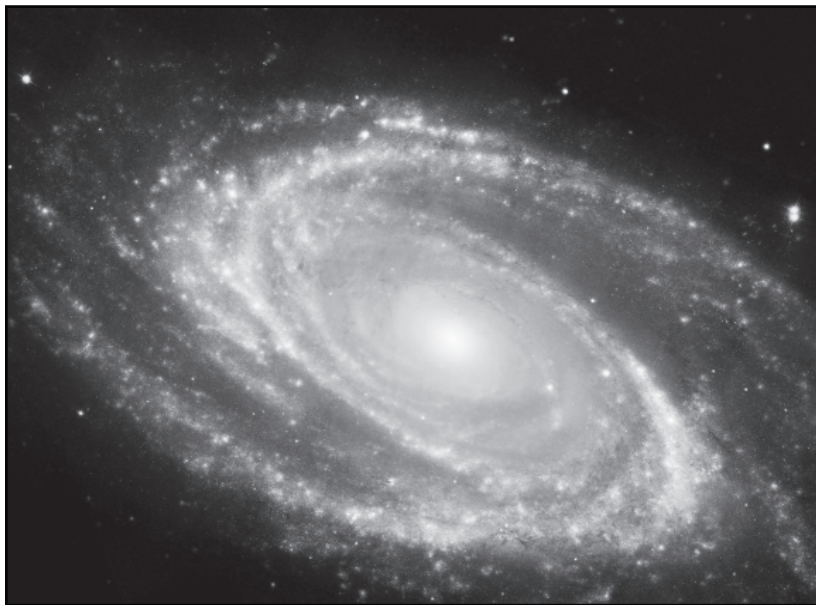
“We Are Made of Star Stuff”

- Analysis of **supernova** remnants reveals that the heavy chemical elements, such as the calcium in our bones and the iron in our red blood cells, were produced by exploding stars long, long ago and then incorporated to form our Solar System about 4.5 billion years ago.
- How did the chemically enriched gases from previous generations of supernovae get incorporated into new planetary systems and life itself? They collected into giant clouds called **nebulae**, and these went through gravitational collapse, forming new stars and planets. The Orion nebula is an example.

- The end product of the gravitational collapse of gas in a nebula is an **open star cluster**. This is a loosely bound group of a few hundred to a few thousand stars, generally somewhat irregular in shape. A great example is the Pleiades, or the Seven Sisters.

Beyond Our Galaxy

- The extreme luminosity of entire galaxies of stars means that we can see some other galaxies with our unaided eyes in the dark night sky. The Magellanic Clouds, for example, are dwarf galaxies that are satellites of the Milky Way.
- In the Northern Hemisphere, we can see the Andromeda galaxy, which is even more distant than the Magellanic Clouds. It's amazing to contemplate that this galaxy is 2.5 million light years away.



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Nearby galaxy, called M81, is about 12 million light years, or 7×10^{19} miles, from Earth.

- If you're unbelievably lucky, you might actually glimpse with your unaided eyes or **binoculars** an object that's several billion light years away: a gamma-ray burst (GRB). This represents a special kind of death of a massive star, where powerful jets of matter and high-energy radiation happen to be pointing in exactly our direction.
- As we'll see later in these lectures, if we expand our vision to radio wavelengths, we can even see the afterglow of the Big Bang—the violent, hot, dense birth of the Universe—in the cosmic microwave background radiation.

Important Terms

Andromeda galaxy: The nearest large galaxy to our own Milky Way galaxy; about 2.5 million light years away.

astronomical unit (AU): The average distance between the Sun and Earth (1.5×10^8 km, or 93 million miles).

apparent brightness: The amount of energy received from an object per second, per square centimeter of collecting area. It is related to luminosity and distance through the equation $b = L/(4\pi d^2)$, the inverse-square law of light.

atmosphere: The layer of air that surrounds Earth's surface, confined mostly to a height of 60 miles or less; usually divided into the troposphere, stratosphere, mesosphere, and (above 60 miles) ionosphere. Other planets have atmospheres, too. The Sun's atmosphere consists of its chromosphere and corona.

binoculars: Two small refracting telescopes joined together, producing magnified and brighter images of distant objects.

celestial sphere: The enormous sphere, centered on the Earth, to which the stars appear to be fixed.

gamma-ray burst (GRB): A brief burst of gamma rays in the sky, now known to generally come from exceedingly powerful, distant objects.

inverse-square law: Decreasing with the square of increasing distance. For example, the brightness of a star is proportional to the inverse-square of distance, as is the gravitational force between two objects.

ionosphere: The fourth major layer of Earth's atmosphere, typically starting at an altitude of about 60 miles. Auroras are usually formed in the ionosphere.

luminosity: Power; the total energy emitted by an object per unit of time; intrinsic brightness.

mesosphere: The third major layer of Earth's atmosphere, above the stratosphere, typically at altitudes of about 30 to 60 miles.

Moon: Earth's natural satellite, about 240,000 miles (60 Earth radii) away. The more generic term "moon" (not capitalized) refers to natural satellites orbiting other planets. Like planets, these moons shine by reflecting sunlight.

nebula: A region containing an above-average density of interstellar gas and dust; often associated with either a cloud in which new stars are being born or the gas ejected from a dying star.

open cluster: A loosely bound cluster of stars, usually consisting of young stars that eventually break away from the cluster.

ozone layer: A layer in the stratosphere, typically 12 to 25 miles above Earth's surface, that contains substantial amounts of ozone (the O_3 molecule), shielding us from much (but not all) of the Sun's ultraviolet radiation. Also, at visible wavelengths, ozone absorbs more red light than blue, leaving blue as the dominant scattered light and causing the deep blue colors of twilight far above the horizon.

planet: A body that primarily orbits a star (so that moons don't count), is large enough to be roughly spherical (typically, larger than about 600 km in diameter), gravitationally dominates its region of space (that is, has largely cleared away other debris), and has never undergone nuclear fusion.

stratosphere: The second major level of Earth's atmosphere, above the troposphere; it is typically about 8 to 30 miles above sea level.

Sun: The star around which Earth orbits.

supernova: The violent explosion of a star at the end of its life.

troposphere: The lowest level of Earth's atmosphere, where almost all clouds and weather-related phenomena are located. Its thickness varies with latitude but is typically about 8 miles. The temperature generally decreases with increasing height in the troposphere.

ultraviolet: Light that has wavelengths shorter than those of visible light but longer than those of gamma rays and X-rays; typically between about 10 and 400 nanometers.

Suggested Reading

Lynch and Livingston, *Color and Light in Nature*.

Naylor, *Out of the Blue*.

Pasachoff and Filippenko, *The Cosmos*.

Questions to Consider

1. Suppose you wish to construct a scale model of the Solar System. The distance between Earth and the Sun (1 AU) is 1.5×10^8 km, and you represent it by 15 km, roughly the size of a reasonably big city. (a) What is the scaled distance of the planet Saturn, which you can easily see in the night sky and whose true distance is 9.5 AU? (b) Earth is about 12,800 km in diameter. How large is Earth on your scale? Compare its size with that of a common object. (c) The Sun's diameter is about 1.4×10^6 km. How large is it relative to Earth? (d) The nearest star, Proxima Centauri, is 4.2 light years away (i.e., 4.0×10^{13} km). How far is this in your scale model? (e) Compare your answer in part (d) with the true distance to the Moon, 3.84×10^5 km. Comment on whether this gives you some idea of the enormous distances of even the nearest stars.

2. If Star Albert is 100 times more powerful (luminous) than Star Einstein, but is 10 times more distant than Einstein, then the apparent brightness of Albert relative to Einstein is (a) 100, (b) 10, (c) 1, (d) $1/10$, or (e) $1/100$.
3. Geologists study different strata on Earth to determine conditions long in the past. For example, fossils in strata dating about 530 million years ago show an enormous diversification of life around that time, the so-called “Cambrian explosion.” How is it that astronomers are able to see parts of the Universe appearing as they were in the past?
4. Walk up the stairs or take an elevator in a tall building. Stop at different floors and look through a window, always in the same direction having an unobstructed view. Does your apparent horizon become more distant as you gain altitude, allowing new objects to become visible?

The Blue Sky, Clouds, and Lightning

Lecture 2

In this lecture, we'll look at some phenomena produced in the lower part of our atmosphere, the troposphere. Some of these are easy to observe, such as the different shades of blue in the sky, the ever-changing clouds, and some forms of lightning. Other phenomena, such as sprites and blue jets, are much rarer but highly rewarding if you're lucky enough to see them.

Earth's Atmosphere

- To a person standing on Earth, the atmosphere looks like a sheet of uniform thickness that extends almost infinitely far in all directions parallel to Earth's surface. But the **density** of the air rapidly decreases with increasing height; the number of **molecules** per unit volume is greatest near Earth's surface.
- Air is about 80% nitrogen molecules, N_2 , and only 20% oxygen molecules, O_2 . There are also trace amounts of other atoms and molecules, such as water vapor, H_2O .
- The atmosphere is almost entirely transparent and intrinsically colorless: Most of the visible sunlight isn't absorbed, and the molecules themselves don't have a specific color. But sunlight does reflect, or scatter, off the air molecules and off dust particles in the air. That's what makes the sky bright.
- The scattered light of the daytime sky is bright enough to overwhelm the light of the background stars. If we didn't have an atmosphere, our sky would be dark, and the stars would be visible even during the day.

Why Is the Sky Blue?

- Light is actually an electromagnetic wave, a combination of electric and magnetic fields whose strength varies with time in a periodic way. The waves consist of self-propagating, oscillating electric and magnetic fields that are perpendicular to each other and perpendicular to the direction of motion.
- The **wavelength** is the distance from one crest to the next or from one trough to the next. Different colors of light correspond to electromagnetic waves having different wavelengths all going at the same speed through a vacuum.
- The Sun, a white star, emits **white light**, which consists of all the colors of the rainbow in different proportions so that the total visible effect perceived by our eyes and brains is white.
- As the white sunlight travels through our atmosphere, some of it gets scattered and bounced. The shorter the wavelength of light, the more it's scattered. This is known as Rayleigh scattering.
- Typical blue light is scattered by molecules 5 times more efficiently than red light. Thus, if you're looking away from the Sun, you see scattered sunlight, which is dominated by blue light, making the sky look blue.
- There are different shades of blue in the sky and different degrees of brightness, depending on when and where you look. When the Sun is low above the horizon, the sky seems to be bluest and darkest near the zenith and appears brighter and more washed out near the horizon.
- The reason for the difference in shades of blue is that closer to the horizon, you're looking through more atmosphere; there are more molecules scattering the sunlight, and that makes the sky brighter near the horizon.

- It's also true that far above the horizon, light reaching you has been scattered only once, but there are multiple scatterings closer to the horizon, where the path length through air is longer.
- In addition to air molecules, particles of dust and fine mist also contribute to scattering and affect the brightness and color of the sky. In general, the bigger the particle, the more total light it scatters.

Aerosols

- **Aerosols** are larger particles of solid or liquid suspended in the atmosphere, roughly 1 to 100 times the wavelength of light. These consist of dust, water droplets, salty or acidic mist, and smoke.
- Aerosols tend to scatter all wavelengths equally efficiently, without a preference for blue light, making the sky look white and hazy, especially near the horizon.
- Around the Sun, there's almost always a bright, colorless circular patch. This is called an **aureole**, and it's largely caused by the forward scattering of sunlight off aerosols.
- In polar regions, where droplets of water have frozen out of the atmosphere and there isn't much pollution, there are few aerosols, so the sky often looks almost completely blue, even next to the Sun.
- **Clouds** consist of large droplets of water or **ice crystals**. These are many times larger than the wavelength of light, so they scatter all colors equally and, therefore, appear almost white.
- By the same token, the Sun seen through relatively thin clouds appears white. Because the particles in the clouds are large and attenuate all wavelengths equally, the Sun retains its true color.

Polarization

- Sunlight is intrinsically unpolarized, which means that the electric fields of different waves oscillate in different directions that are perpendicular to the direction of motion. But if you pass the light through a polarizing filter, it tends to transmit light whose electric field is vibrating in a particular direction.
- **Reflection**, or scattering, also tends to polarize light. Light whose electric field is in the plane defined by the incoming and outgoing rays doesn't scatter as well as light whose electric field is perpendicular to that plane.
- The amount of reflected light and, hence, the glare can be diminished by looking through polarizing sunglasses. Only light whose electric field is vibrating in the direction perpendicular to the ground is allowed to pass through these glasses. This reduces the glare from horizontal surfaces, such as roads or lakes.
- **Airlight** is also partly polarized because it's scattered light. The largest amount of polarization is for rays coming toward you from a direction perpendicular to the Sun's direction. Closer to the Sun's direction, the polarization is less; it's also less directly opposite the Sun.

Clouds

- Clouds are produced when moisture in the air condenses, forming either water droplets or ice crystals. Condensation occurs when the air temperature falls below the dew point, because cold air can't retain as much moisture as warm air can.
- Cirrus clouds are the first of the three main types of clouds. These are thin, wispy clouds that often appear feathery or fibrous.
- Stratus clouds look like horizontally extended layers or sheets, but they are not very thick in vertical height.



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Clouds are classified into types, or genera, by their distance above sea level as well as their shapes.

- Cumulus clouds are quite extended in the vertical direction and look heaped or puffy.
- These three major categories of clouds have a total of 10 specific, generally recognized types, or genera, analogous to those in the plant and animal kingdoms. The most important characteristic in defining the various genera is the **altitude** above sea level of the cloud base.
- **Fog** consists of tiny droplets of water that have condensed out of moist air. It is distinguished from clouds in that it refers to low-lying material whose moisture was produced locally, from, say, a lake.
- Contrails can be thought of as artificial clouds trailing behind the airplane that produced them. They form when the hot, moisture-laden exhaust from a jet engine expands and cools rapidly. The temperature can fall below the dew point, so the water vapor condenses to droplets or even ice crystals.

Lightning

- **Lightning** is a powerful electrical discharge that's often seen coming from cumulonimbus clouds and is accompanied by **thunder**.
- Thunder occurs when the electric current in a lightning bolt suddenly heats the air in the discharge channel to temperatures of about 30,000–50,000 degrees Fahrenheit, causing it to glow by incandescence. This superheated air expands supersonically and sends a shock wave through the atmosphere; that's what we hear as thunder.
- The time delay between lightning and thunder is about 5 seconds per mile. The flash of light travels at a speed of 186,000 miles per



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Lightning is a form of static electricity, albeit on a monumental scale. In both cases, the surrounding air is ionized, and an electrical current is created.

second, so it reaches us almost instantaneously. But the speed of sound in air is only about 1100 feet per second, which equals about 1 mile every 5 seconds.

- How does lightning form? A good bit of charge separation must be present in order to have a strong enough electric field to produce the ionization of air needed for a current. Most frequently, such charge separation occurs in cumulonimbus clouds.
- In all cases of lightning, collisions among the particles strip electrons off of some atoms, leaving them positively charged and providing a negatively charged excess of electrons on other particles. In this way, a lightning bolt is a greatly scaled-up version of the discharge you experience with static electricity in your home.
- The details of how charge separation occurs in thunder clouds aren't fully known. According to one idea, if there's a strong updraft, water droplets can supercool and freeze when they hit ice crystals, forming soft, hail-like pellets called **graupel**.
- When the graupel collides with other ice crystals, charge separation can occur. Usually, the graupel becomes negatively charged and the crystals, positively charged. The strong updrafts move the lighter crystals upward, making the top of the cloud positively charged, and the heavier graupel falls, carrying negative charge with it. This process of charge separation produces a strong electric field within the cloud.
- A sudden discharge can occur inside the cloud, and sometimes, this discharge reaches the ground. The negatively charged cloud bottom induces a positive charge on Earth's surface, creating a strong electric field.
- In this situation, a path of **ionized** air called a **stepped leader** starts to form near the cloud bottom, making its way toward the ground in a series of discrete jumps. After the negative leader has made some progress and the electric field between it and the ground increases, an oppositely directed positive streamer starts moving up from the ground.

- Eventually, the upward-moving positive streamer connects with the downward-moving stepped leader, forming a path of ionized air between the cloud and the ground. Current can easily flow along this path of lowest resistivity. A much larger current can then flow up from the ground and into the cloud, forming an electric discharge. This is what forms the rapid, easily visible lightning bolt.
- It has long been thought that the flickering of a typical lightning bolt is caused by different strokes. In fact, recent videos reveal that the current goes back and forth along the discharge channel many, many times.
- There are many different types of lightning besides the well-known cloud-to-ground lightning, including intra- and inter-cloud lightning, forked lightning, bead lightning, and even ground-to-cloud lightning.

Other Electrical Phenomena

- **St. Elmo's fire** is seen as a faint bluish-violet glow that surrounds tall, pointy objects during thunderstorms. It occurs when a strong electric field forms around a sharp-edged object that is sufficient to ionize the adjacent air and make it glow.
- **Sprites** are reddish-orange flashes that last just a few milliseconds and are the result of electrical discharges of cold, ionized gases that occur above thunderstorm clouds in the upper atmosphere. They are triggered by rare positive lightning discharges between a thundercloud and the ground, but they're much higher up, usually in the mesosphere.
- One final interesting but rare electrical phenomenon in the upper atmosphere is the **blue jet**. This is similar to upward-facing lightning, but it is longer and has a bluish color.

Important Terms

aerosol: Small particles of liquid or solid, typically about 1 to 100 micrometers in diameter, suspended in Earth's atmosphere.

airlight: Sunlight that has been reflected (scattered) by air molecules in Earth's atmosphere. It tends to be blue because Rayleigh scattering is more efficient at short wavelengths than at long wavelengths.

altitude: The number of degrees between an object and the horizon directly below it; the zenith has an altitude of 90 degrees, for example. Alternatively, the height of an object (such as a cloud) above Earth's surface, typically measured in miles or kilometers.

aureole: A circular patch of light around the Sun, usually colorless, formed by sunlight that has been forward-scattered by aerosols in Earth's atmosphere. Also, the central patch of colorless light in a lunar or solar corona formed by the interaction of sunlight with water droplets in clouds.

blue jet: A rare form of upward-moving lightning that starts from the top of a thundercloud and has a bluish color.

clouds: Regions of the atmosphere where water vapor has condensed to form water droplets or ice crystals. The three main cloud types are cirrus (thin, wispy, high-altitude clouds consisting of ice crystals), stratus (horizontally extended layers or sheets but not very thick; they consist of water droplets and/or ice crystals), and cumulus (heaped or puffy clouds having considerable vertical extent; they consist of water droplets).

density: Mass per unit volume or, in some cases, the number of particles per unit volume (usually referred to as "number density").

fog: Tiny (typically 0.05–0.1 mm) drops of water that have condensed out of moist air. In some cases, fog is simply the inside of a cloud, such as a stratus cloud. Generally, however, fog refers to condensation that forms in air whose moisture was produced locally, such as from a lake or wet ground.

graupel: Soft, hail-like pellets that form in a cloud having a strong updraft, where water droplets can supercool and then freeze when they hit ice crystals.

ice crystals: Frozen water, which takes on a fundamentally hexagonal shape because of the structure of the water molecule, H_2O . Simple ice crystals are typically flat plates or long, thin columns, like pencils. Snowflakes tend to be larger and more complex, though still having hexagonal symmetry.

ionized: Having lost at least one electron. Atoms become ionized primarily by the absorption of energetic photons and by collisions with other particles.

lightning: A powerful electrical discharge that generally forms from cumulonimbus clouds and is accompanied by thunder. There are many types, such as the familiar cloud-to-ground lightning, cloud-to-cloud, ribbon, sheet, bead, and others.

molecule: The smallest distinct unit of a given substance; it consists of at least two atoms. For example, the water molecule is H_2O .

reflection: The “bouncing” of a light wave off of a surface, so that it changes direction. In all cases, the reflected wave makes the same angle as the incident wave, relative to a line perpendicular to the reflecting surface.

sprite: A flash of light lasting a few milliseconds, high in the upper atmosphere (mesosphere) above rare positive lightning discharges in thunderstorms. It is an electrical discharge in cold ionized gases.

St. Elmo’s fire: A faint, bluish-violet glow that can surround tall, pointy objects, such as lightning rods and spires, during thunderstorms.

stepped leader: A path of ionized air generally having a negative charge that starts to form near the bottom of a cloud, making its way downward toward the ground in a series of discrete jumps.

thunder: The sound that is formed by lightning when superheated air expands supersonically, sending a shock wave through the atmosphere.

wavelength: The distance over which a wave goes through a complete oscillation; the distance between two consecutive crests or two consecutive troughs.

white light: Sunlight or any other light whose spectrum contains all the colors of the rainbow with roughly the same proportions as in sunlight.

Suggested Reading

Hamblyn, *The Cloud Book*.

Hoeppe, *Why the Sky is Blue*.

International Cloud Atlas.

Lewin, *For the Love of Physics*.

Lynch and Livingston, *Color and Light in Nature*.

Minnaert, *Light and Color in the Outdoors*.

Naylor, *Out of the Blue*.

Questions to Consider

1. Suppose air molecules and dust didn't scatter (reflect) sunlight at all. How bright would the sky look in directions away from the Sun, and what color would it be?
2. In mountainous regions like the Sierra Nevada range in California, puffy white cumulus clouds often form in the early to midafternoon, but go away shortly after sunset. Why do you think this is the case? What is causing those clouds to initially form?

3. Make a habit of looking at the sky and noticing the many different varieties of clouds. Consult a cloud atlas to learn their names.
4. If you live in an area with thunderstorms, watch one for a while from the safety of your home, through a window. Do you notice any patterns among the lightning bolts? How often do you see intercloud or intracloud lightning (in some cases just a brief brightening of the cloud, sheet lightning) compared with cloud-to-ground lightning?

The Rainbow Family—Sunlight and Water

Lecture 3

The interaction of sunlight with water produces a variety of colorful phenomena in the sky. If the speed of light weren't slower in water than in air and if the exit angles for a given wavelength of light didn't bunch up at a particular value, we wouldn't be treated to such wondrous sights as rainbows, coronas, and glories. In this lecture, we'll learn the physical explanations for these beautiful occurrences in the sky.

What Produces a Rainbow?

- The explanation of how **rainbows** are produced depends on the fact that light entering and exiting water droplets, such as those in clouds, is dispersed into its component colors (wavelengths).
- The speed of light is substantially slower in glass or water than in air, and this causes light to bend, or refract, when entering or exiting glass and water drops. Further, the speed of different wavelengths varies slightly. Violet light, for example, has a shorter wavelength and travels through glass or water more slowly than red light, so violet light is bent more.
- When incoming sunlight hits near the top of a single spherical **raindrop**, some of it bounces from the surface and heads back out into the air; in other words, it is reflected. But the rest of the light enters the raindrop and gets **refracted**.
- This dispersed light heads through the raindrop and hits the back side, and some of it exits into the outside air. The rest reflects off that back side and goes through the raindrop again until it reaches the boundary. Some of it is reflected, but the rest exits the drop and gets further refracted, spreading out the colors even more.

- Violet light exits at a shallower angle than red light relative to the line along which the light first entered the raindrop. This means that the violet ray will seem to come from lower in the sky than the red ray when they enter the eye.
- When we have a whole collection of raindrops, each of them will bend the Sun's rays into a **spectrum** of colors, but the angle that each ray is bent depends on its color. In the case of a rainbow, red light comes in from an angle of 42 degrees relative to the rainbow's center, and violet light comes in at an angle of about 40 degrees.
- The rainbow's center of curvature is at the **antisolar point**, the direction that's exactly opposite the Sun. You can find your own antisolar point by facing away from the Sun and drawing an imaginary line from the Sun, through your head, and on to your head's shadow.
- The drops that form, say, the red part of the rainbow are completely different from those that produce the violet part for a given observer. And the same drops that contribute to the violet part of the rainbow as seen by you will produce the red part of someone else's rainbow who is viewing it from a different position.
- Nevertheless, the angle between the red part of the rainbow and your antisolar point is always 42 degrees, and the angle between the violet part and your antisolar point is always about 40 degrees.

Why Do the Rays “Bunch Up”?

- It might seem odd that the rays of a given color “bunch up.” After all, a red ray exiting the drop could be sent into many possible directions, depending on where it enters the drop.
- While red rays can indeed exit the drop at many different angles (38 degrees, 39 degrees, and so on), there is a maximum angle of 42 degrees. This means that the red rays get concentrated at an angle of

42 degrees from the antisolar point. Many rays are exiting in nearly the same direction, producing a relative excess of light there.

- Note, too, that when light is passing through water drops, no color of visible light gets bent by more than 42 degrees. That means that the red part of the rainbow is pure red, with no contamination from other colors.
- Since no color of visible light contributing to the primary rainbow gets bent by more than 42 degrees, the outside of the rainbow looks relatively dark. Conversely, since all colors of light can exit raindrops at angles smaller than 40 to 42 degrees, there will be a relative excess of light within the rainbow, closer to the center.

The Geometry of a Rainbow

- A rainbow is actually a cone, since the angles of 40 to 42 degrees can be anywhere around the antisolar point. Of course, the ground cuts off much of it, so we don't see a full circle. In fact, under normal conditions the most we see is a semicircle.
- We can see a semicircular bow when the Sun is right on the horizon, near sunrise or sunset. Such bows can sometimes appear monochromatic, with quite a bit more orange and red than usual.
- When the Sun is well above the horizon, the antisolar point must be well below the horizon, so a smaller part of the semicircle is visible. If the Sun is at least 42 degrees above the horizon, then none of the rainbow will be visible, since it's completely below the horizon.
- On rare occasions, the full circle can be seen from an airplane or helicopter. To see most or all of the circular rainbow, the drops have to be quite close to you, such as if you're hovering above the spray of a waterfall.
- For you to see a rainbow, there must be water drops in a particular direction: 40 to 42 degrees from the antisolar point. Direct sunlight

must hit them, and there can't be anything along your line of sight blocking them.

Varieties of Rainbows

- Near the time of a full Moon, you may be able to witness a lunar rainbow, usually called a moonbow. Moonbows are faint, since the sunlight reflected from the Moon is so much fainter than direct sunlight. They usually appear white because our eyes simply are not sensitive to color in faint-light conditions.
- Rainbows called fogbows can also be formed in fog. A fogbow has a slightly smaller **angular size** than a rainbow, less than 42 degrees, and it's somewhat wider. There is also less color than in a rainbow and it appears more diffuse.
- Below a normal rainbow, you can sometimes see a **reflected rainbow** in a body of water that's in front of you, opposite the Sun. Actually, the visible reflection is not that of the primary bow that you can see but, rather, of a more distant rainbow that you can't see. The angle is wrong for you to see the second rainbow directly, but its reflection is visible.
- In addition to a rainbow reflected on water, there can also be a **reflection rainbow** in the sky created by light reflecting from water. This can be produced if there is a nearby body of smooth water that is behind you, in the general direction of the Sun.

The Secondary Rainbow

- Under some conditions, you can see a secondary rainbow that is fainter and larger than the primary bow. The colors in a secondary rainbow are in the reverse order of the primary.
- To see how the secondary rainbow is formed, consider a single raindrop. Incoming sunlight hits near the bottom of the drop rather than near the top, as with the primary bow. Some of it is reflected

from the surface and heads out into the air. But the rest enters the drop, gets dispersed into its component colors, and heads to the back side of the drop, where some of it exits and the rest is reflected.

- The reflected light goes through the drop and hits another side, and some of it passes through the boundary and exits into the air, but the rest is reflected once again, a second internal reflection.
- The doubly reflected light goes through the drop and hits another side. Some of it passes through the boundary and exits into the air, with the colors becoming even more spread out in the process.
- In this case, the violet light exits at a steeper angle than the red light. Exactly the opposite occurred for the light that exited after only one internal reflection. This means that the violet ray will come from higher in the sky than the red ray when they enter your eye.



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The portion of a rainbow visible above the horizon is just a slice from a full circle. That circle, in turn, is a slice out of a cone, with the Sun at its apex.

- Notice, too, the steep angle of all the rays relative to the antisolar point. From red to violet, the light enters the eye at angles of about 51 to 54 degrees relative to your antisolar point. Red light rays are concentrated at angles of 51 degrees because light can exit the drop at a minimum angle of 51 degrees but no smaller.
- Since violet comes in at a somewhat steeper angle of 54 degrees, the violet part of the secondary bow will be on the outside, and the red part will be on the inside.

Supernumerary Bows

- **Supernumerary bows** or arcs tend to appear when the sunlight is very bright and the secondary bow is also present. These are subtle bands inside the main bow, right next to the violet part, that alternate slightly between brighter and darker. Supernumerary bows can be explained by a wave theory of light.
- Light can be considered a set of electric and magnetic fields that alternately become stronger and weaker, making waves that oscillate in directions perpendicular to the direction of motion. If two waves are in phase (their wave crests are lined up), they reinforce each other, producing even larger oscillations with the same wavelength. Because this makes the light brighter, it's called constructive interference.
- Destructive interference occurs when the crests of one wave are aligned with the troughs of the other. The crests and troughs add up to zero all along the wave, so there's no visible light whatsoever. If the alignment isn't perfect, there's partially destructive interference, which allows you to see some light.
- With supernumerary bows, two rays enter a raindrop at two slightly different locations yet have the same exit angle. Because the two paths of these rays inside the drop aren't exactly the same, they can get out of phase.

- When they emerge out of phase, they create destructive interference. Rays exiting at slightly different angles can constructively interfere, producing a bright part of the rainbow. This results in a series of alternating bright and dark bands. This kind of interference among light waves is called diffraction.

Diffraction in the Sky

- **Diffraction** of moonlight by water droplets in some types of clouds can produce a lunar crown called a **corona**. What's needed to form a diffraction corona is tiny droplets of water or ice crystals of roughly uniform size inside clouds.
- By the very same process as for the Moon, a diffraction corona can form around the Sun if there are altocumulus clouds along the line of sight or, more rarely, cirrocumulus clouds with some ice crystals.
- Clear separation of the main colors in a corona occurs when the droplets in the cloud are all nearly the same size. But if the average size of the water droplets changes randomly within the cloud, the corona becomes more unstructured, producing **cloud iridescence**.
- Finally, the phenomenon known as the **glory** is a ring or set of rings on clouds in the direction opposite the Sun, similar to an antisolar corona.

Important Terms

angular size: The angle in the sky taken up (subtended) by an object, as seen by us. The angular distance from the horizon to the zenith is 90 degrees.

antisolar point: The direction in the sky that is directly opposite the Sun, as seen by a given observer from a given location. It coincides with the shadow of the observer's head.

cloud iridescence: Colorful bands or spots in clouds, formed by diffraction of sunlight by water droplets spanning a range of sizes in clouds. Closely related to the solar corona that is formed when droplets of uniform size diffract sunlight but more chaotic in appearance.

corona: The very hot, tenuous, outermost region of the Sun, seen during a total solar eclipse. Also, a colorful set of rings around the Sun or Moon, produced by the interaction of light with uniformly sized water droplets in tropospheric clouds. The smaller the droplets, the larger the radius of the corona.

diffraction: A phenomenon affecting light as it passes any obstacle, spreading it out and producing an interference pattern. This occurs best when the size of the obstacle is roughly comparable to the wavelength of light.

glory: An often colorful halo of light around the shadow of an object projected on a cloud or fog; caused by the refraction, reflection, and interference of light passing through water droplets.

rainbow: The spectrum of sunlight produced by the dispersion of light passing through raindrops. The primary rainbow is the inner one; its colors go from violet on the inside (at an angle of 40 degrees from the antisolar point) to red on the outside (at an angle of 42 degrees from the antisolar point). The outer, secondary rainbow has reversed colors ranging from about 51 to 54 degrees.

raindrops: Generally spherical drops of water falling to the ground from clouds; most of them are between 0.1 and 5 millimeters in diameter, though those forming rainbows are typically 1–2 millimeters in size.

reflected rainbow: A rainbow that appears as a reflection in the surface of a body of water roughly opposite the Sun. It is not the reflection of the primary bow visible above ground but, rather, of another more distant rainbow that is not directly seen.

reflection rainbow: A rainbow in the sky formed after sunlight reflects off the surface of a body of water that is behind the observer, in the Sun's

general direction. It appears roughly opposite the Sun, just outside the normal primary rainbow, merging with the primary bow near the ground.

refraction: The bending of light as it passes from one medium to another having different properties. The speed of light in the medium is equal to the vacuum speed divided by the index of refraction.

spectrum: A plot of the brightness of electromagnetic radiation from an object as a function of wavelength or frequency.

supernumerary bows: The faint light and dark bands bordering the inside edge of the primary rainbow, produced by constructive and destructive interference.

Suggested Reading

Gleick, *Isaac Newton*.

Lewin, *For the Love of Physics*.

Lynch and Livingston, *Color and Light in Nature*.

Minnaert, *Light and Color in the Outdoors*.

Naylor, *Out of the Blue*.

Questions to Consider

1. Suppose water drops refracted all wavelengths of visible light exactly the same way, for example by the amount the red ray is normally refracted. Would rainbows still be possible? If so, what would they look like?
2. Get a camera polarizing filter or polaroid sunglasses and look through it at a rainbow while rotating it to different angles. How does the rainbow's appearance change? Do you see exactly the same effects when you look at different parts of the rainbow?

3. Examine changes in the appearance of a lunar corona while clouds are drifting by.
4. In what ways is a glory similar to a solar corona? In what ways does it differ? Which one do you expect to be more polarized?

Solar Halos—Sunlight and Ice Crystals

Lecture 4

In the last lecture, we saw how sunlight interacts with liquid water drops in the lowest part of the troposphere to form beautiful rainbows, coronas, and iridescent clouds. But higher in the atmosphere, or at higher latitudes, or when it's a colder season, sunlight interacts with frozen ice crystals instead of raindrops. As we'll see, this interaction can produce a wide variety of amazing phenomena, including solar halos, sundogs, and arcs.

The Interaction of Sunlight and Ice

- The 22-degree solar halo is just one example of the amazing features of the sky caused by the interaction of sunlight and ice. Though related to the rainbow, it's formed by sunlight passing through hexagonal ice crystals in cirrus or cirrostratus clouds.
- In addition to the 22-degree halo, there's a much fainter 46-degree halo, and within or next to the halos, at the altitude of the Sun, are parhelia, more commonly known as sundogs.
- At the Sun's altitude, we can also occasionally see a **parhelic circle** going all the way around the sky. And beyond the halos, there are the **tangent** and **circumzenithal arcs**.

Basic Principles

- Simple ice crystals are the key to understanding all of these phenomena. Due to the nature of water molecules, ice crystals take on a fundamentally hexagonal shape, and perfect ones (those formed under ideal conditions directly from water vapor, not liquid water) are quite symmetric.

- A diagram of a water molecule shows 1 oxygen atom with 2 hydrogen atoms bonded to it in a familiar “Mickey Mouse ears” pattern. The angle between the oxygen and the 2 hydrogen atoms is always 104.5 degrees.
- Though electrically neutral overall, the molecule is said to be polar; the oxygen side is slightly negative, and the hydrogen side is slightly positive. This makes water molecules attract each other.
- At low temperatures, when motions are slow, water molecules join together to form a crystalline lattice of hexagons. The adjacent faces of hexagons form 120-degree angles, yet the angle in water molecules is only 104.5 degrees.
- To form the lattice, the adjacent oxygen atoms take on an up-down pattern; they’re not in the same plane. The upshot is that when water molecules bond rigidly, they naturally form hexagonal crystals.
- Despite this fundamental hexagonal symmetry, the detailed shapes that result when many molecules come together to form a snowflake have an almost infinite variety. Each snowflake has a shape that is a consequence of the varying temperature and humidity of every location it encountered while forming.
- High in Earth’s atmosphere, when ice crystals slowly form from water vapor at low densities, small, relatively simple types of crystals can appear. Cirrus clouds, unlike most other clouds, consist of ice crystals. Each crystal was made by the condensation of water vapor around a bit of dust, pollen, or other aerosol particle.
- An ice crystal can be a thin, hexagonal plate. Viewed from above, you can see that the angle between adjacent sides is 120 degrees. If you were to extend two alternate sides, they would come together at an angle of 60 degrees. Thus, light entering one face and exiting from the alternate face is effectively going through a 60-degree prism.

- This light is refracted and dispersed into its component colors, as we discussed in the previous lecture. There is also a 90-degree angle between the plate's side and end faces, and light passing through it also gets refracted and dispersed.
- In addition to a plate, an ice crystal can be a long, thin, hexagonal column or rod that looks like a short pencil. The variety of shapes is caused by differences in the conditions in which the crystals form. Ice crystals can also take on certain preferred orientations while falling through the air.
- Even if many of the crystals are imperfect, quite a few transparent plates or columns having smooth sides and crisp angles may exist in a cloud, and from these, we get some amazing sights.

The 22-Degree Halo

- Spots and arcs are formed when light passes through ice crystals, undergoing reflection and refraction. The most common such sight is the 22-degree halo around the Sun. It looks like a diffuse ring around the Sun, with a radius of about 22 degrees (roughly half the width of a rainbow).
- The 22-degree halo forms when light goes through long, thin columns of crystals. Light enters one long face and exits from the alternate long face, two faces over. Such crystals occur in cirrostratus clouds.



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Ice-crystal halos are similar but generally smaller cousins to rainbows.

- To get a bright, complete halo, you need a reasonably uniform distribution of randomly oriented columns. This can occur if the crystals spin in a variety of directions as they fall.
- Light enters the crystals at different locations and gets refracted, then exits the crystals over a wide range of directions. If all of the exit angles were equally represented, we wouldn't see a halo, but in fact, some exit angles are favored over others, as we saw with rainbows.
- Light exits from one of the long faces at different angles, depending on the angle at which it entered the crystal (the angle of incidence), but there is a minimum deflection of 22 degrees for light that enters at a particular angle of incidence. This results in a concentration of rays near that exit or deflection angle of 22 degrees, just as light bunched up at 40 to 42 degrees when forming a rainbow.

Colors in the Halo

- The main colors of the 22-degree halo, and of halo phenomena in general, are red, orange, and yellow. There are several reasons for this.
- First, ice crystals spread out shorter wavelengths of light more than longer wavelengths, so the longer wavelengths are more concentrated and appear brighter.
- Second, if a halo is seen against a background sky that's typically blue, the blues and greens tend to blend in more than the longer wavelengths.
- Third, if a halo is formed when the Sun is getting low, more of the blues and greens have been filtered out by the atmosphere. This means that relatively more light at longer wavelengths reaches your eyes.

- Fourth, because of the way light is bent by ice crystals, the blues and greens are always accompanied by some longer wavelengths, and this tends to wash out those colors, making them appear whitish. The red and orange colors are relatively pure and appear more vivid in the sky.
- The 22-degree solar halo is visible perhaps one or two times per week at middle latitudes. This halo can also be seen around the Moon, particularly when it is full or nearly full, but it's much fainter than the solar halo.

The 46-Degree Halo

- Related to the 22-degree solar halo is the far less common 46-degree halo. Again, what's needed to form this halo are cirrus or cirrostratus clouds with thin, pencil-shaped columns having random orientations.
- Light enters a long face and exits from the end of the column. There's a 90-degree angle between the two faces, which is analogous to the 60-degree angle between alternate long faces that we saw in the 22-degree halo.
- Light exits the end face along different angles, depending on the angle at which it entered. There is a minimum deflection of 46 degrees, creating a bunching up of rays at this exit or deflection angle relative to the Sun's direction and a concentration of light near this angle.
- The 46-degree halo is fairly rare. The crystals forming it must have very smooth sides and ends, and this occurs only when the crystals grow very slowly.

The Parheliion

- The **parheliion** (meaning “beside the Sun”) is a bright spot slightly outside the position of the solar 22-degree halo and sometimes overlapping it at the Sun’s elevation above the horizon. Parhelia are sometimes called mock suns or sundogs.
- Parhelia are formed by flat, plate-like ice crystals. Light enters one of the short vertical faces, is refracted, and exits through an alternate face. There’s a concentration of light deflected by about 22 to 24 degrees, similar to the 22-degree halo, but here, the orientation of the plates must be roughly horizontal, not random.
- Thin plates tend to align this way when falling slowly through the atmosphere, generally making sundogs more obvious than other parts of the 22-degree halo because there is an excess of such plates.
- When the sunlight is bright enough, the sundog shows the colors of the rainbow. The inner part, closest to the Sun, is red and bright, and progressively shorter wavelengths are seen farther out.
- Due to details of the light path and refraction, parhelia can form only when the Sun is less than about 60 degrees above the horizon, and they are brightest when the Sun is near the horizon.
- Just as there can be lunar 22-degree halos, sometimes, lunar versions of parhelia appear. These are paraselenae, or moondogs.

Subsuns and Sun Pillars

- Horizontal, plate-like crystals also produce other interesting phenomena called **subsuns** and **sun pillars**.

- A subsun, which looks like a pillar below the Sun, can occur when thin, nearly horizontal plates are in the air, in the direction below the Sun in the sky, usually near sunrise or sunset. Light is simply reflected upward off the tops of the flat ice crystals, making the crystals appear bright.
- Sunlight reflecting off water having a rough surface illustrates some of the principles of subsun formation. The reflection is called a **glitter path**, and the subsun is essentially the Sun's glitter path in the air.



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- Plates of flat ice crystals suspended in the air create the sun pillar effect.
- In a similar way, there can also be upward-facing sun pillars. As with subsuns, sun pillars are produced by nearly horizontal plates in the air, but this time, in the direction above the Sun rather than below it. The bottoms of the ice crystals reflect sunlight downward.

Other Halo Phenomena

- The parhelic circle forms mostly by reflection off the short vertical sides of plate-like crystals that are horizontal or nearly so. Sunlight comes in from one side and reflects off the ice crystals all the way around the observer, if these crystals are present. Usually, however, the crystals are missing in some directions in the sky, so the parhelic circle is incomplete.

- If the Sun is close to the horizon and the 22-degree halo is easily visible, two wing-like features may appear at the top of it. These are called upper tangent arcs. The tangent arcs are formed by long, pencil-like columns falling horizontally through the air.
- The size and shape of the tangent arcs depend on the Sun's position in the sky. As the Sun rises higher above the horizon, the lengths of the upper tangent arcs grow, and they flatten out. When the bottom part of the 22-degree halo is above the horizon, two lower tangent arcs appear.
- When the Sun is sufficiently high, at least 40 degrees above the horizon, the upper and lower tangent arcs can join together, forming a **circumscribed halo**.
- A potentially very colorful arc partly circles the zenith, the highest point in the sky. For this circumzenithal arc to be seen, the Sun must be pretty low, at most 32 degrees above the horizon. The circumhorizontal arc is a related phenomenon that can be seen only when the Sun is at least 58 degrees above the horizon.
- If cirrus clouds are widely spread out in the sky and contain a mixture of crystals having different shapes, sizes, and orientations, then many different types of halos can be seen simultaneously. Depending on the specific conditions, there can be related phenomena, as well, such as halos inside the 22-degree halo or rare types of arcs.

Important Terms

circumhorizontal arc: A band of light having the colors of the rainbow, parallel to the horizon and not much above it, at least 46 degrees away from the Sun. Formed by sunlight passing through roughly horizontal, plate-like ice crystals.

circumscribed halo: A rare halo around the common 22-degree solar halo, formed when the Sun is sufficiently high above the horizon and the upper and lower tangent arcs grow longer and join together.

glitter path: Sunlight or moonlight (or light from another source, such as a lamp) reflecting off the rough surface of water or snow, forming a column of light that can shimmer with time.

parhelic circle: A faint circular band (or part of such a band) in which the sky appears slightly brighter than in neighboring regions, at the Sun's altitude above the horizon; a horizontal extension of the parhelia. Formed by sunlight being reflected mostly by the vertical sides of horizontal, plate-like ice crystals.

parhelion: Sometimes called a sundog or mock Sun; a bright, often colorful patch of light about (or slightly more than) 22 degrees from the Sun, at the Sun's altitude above the horizon. Parhelia can form on either side of the Sun when light passes through roughly horizontal, plate-like, hexagonal ice crystals.

subsun: A sun pillar below the Sun in the sky, best visible shortly before sunset or shortly after sunrise. Formed by sunlight reflecting off horizontal, plate-like ice crystals.

sun pillar: A faint pillar of light above the Sun in the sky, best visible after sunset; formed by sunlight reflecting off horizontal, plate-like ice crystals. It can also appear below the Sun, in which case it is often called a subsun.

tangent arc: A faint arc of light tangent to and outside the 22-degree halo; called the upper tangent arc if above the Sun and the lower tangent arc if below it. Formed by sunlight passing through long, thin ice crystals that are roughly horizontal.

Suggested Reading

Lynch and Livingston, *Color and Light in Nature*.

Minnaert, *Light and Color in the Outdoors*.

Naylor, *Out of the Blue*.

Questions to Consider

1. What if ice crystals were fundamentally square instead of hexagonal, forming cubes, or plates shaped like dominos, or long four-sided pencils. Do you think any members of the halo family would still form? If so, would they appear in the same parts of the sky as we observe for real ones?
2. Get a camera polarizing filter or polaroid sunglasses and look through it at a 22-degree solar halo while rotating it to different angles. Does the halo's appearance change?
3. Try searching for halo phenomena whenever you see cirrostratus clouds in the sky. Are you surprised by the number of times you find one, even on days when the air temperature near the ground is quite high?

The Colors of Sunrise and Sunset

Lecture 5

Although the Sun is a white star, it appears yellow, orange, or even red at sunrise and sunset because its color is modified as its light rays pass through the atmosphere. This seemingly mundane observation results in a wondrous display of color in the sky, one that you can see twice on almost every day of the year. In this lecture, we'll learn the origin of the colors of sunrise and sunset, explore cloud colors, and identify the best times and places to see long, dramatic sunsets and the elusive green flash.

The Progression of Sunset

- Sunset and sunrise show essentially the same phenomena but in the reverse order and at opposite horizons.
- The Sun appears yellow, orange, or even red at sunset because as its light path through the atmosphere increases, there's progressively more scattering of blue, green, and violet light away from the line of sight. Fine particles, such as dust and smoke in the air, also reflect the shorter wavelengths of light more than red.
- On rare occasions, the Moon, and even the Sun, can appear to be blue. This occurs when the atmosphere contains lots of dust or smoke particles having a size slightly bigger than the wavelength of red light and almost no particles of other sizes. The yellow to red light from the Moon is preferentially scattered away from our line of sight, leaving primarily blue light.
- When the Sun is near the horizon, yellow, orange, and red light streams through the air and illuminates the sky. The western horizon looks orange or red when the Sun is setting. This bright glow in the west is called the **twilight arch**. The dominant color of the Sun changes from yellow to orange to red as it moves closer to the horizon because the light is passing through more air.

- To the east, there can be a pinkish glow known as the **antitwilight arch** or the Belt of Venus. Here, what we're seeing is higher parts of the atmosphere illuminated by direct sunlight that has been filtered by passing through air.
- If you look toward the east shortly after sunset, you may see a dark blue band just below the Belt of Venus and above Earth's surface. This is Earth's shadow being cast on the atmosphere.
- As the Sun dips farther below the horizon, the dark bluish band of light in the east becomes wider, and the boundary with the Belt of Venus becomes less distinct. Eventually, the boundary fades away, and much of the sky becomes relatively dark.
- When filtered light from the nearly setting Sun hits mountains, glaciers, or other land objects, it can make them glow with warm colors. This is known as **alpenglow**.



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At sunset, clouds take on more dramatic hues because sunlight passes through more layers of atmosphere.

- As the Sun dips lower below the horizon, the bright twilight arch begins to fade and goes from yellow to orange to red. But the color of the sky overhead and in a broad region surrounding the zenith will remain a deep blue. That's because light is being scattered by molecules high in the atmosphere.
- If you're lucky, you might see a phenomenon known as **purple light** about 20 to 40 minutes after sunset at mid-northern latitudes. This is a diffuse purple glow in the western sky above the twilight arch. It results from a combination of blue light Rayleigh-scattered by relatively low parts of the atmosphere, and also scattering by dust particles in the stratosphere.

Sights in the Sky at Sunset

- When clouds are present in the sky, the rays of filtered light bounce off the clouds, creating beautiful views. The precise color we see in clouds at sunset depends on such factors as their horizontal location, altitude, and shape, and on the amount of particulate matter in the atmosphere.
- The colors in the clouds can change rapidly as the Sun approaches the horizon and goes farther below it because a given cloud receives rays that have traveled through different paths. The clouds themselves also change location.
- Many people look only toward the Sun and its vicinity around sunset, but be sure to look in other directions, as well—perpendicular to the Sun's direction or even opposite the Sun.
- From an airplane, especially on a polar route, you can sometimes see polar stratospheric clouds that form during the polar winters at altitudes of about 10 to 16 miles. They're also called **nacreous clouds** because they seem iridescent and resemble mother of pearl.

- The highest clouds in the atmosphere, roughly 50 miles above sea level, are called **noctilucent clouds**. These thin, ghostly clouds can reflect sunlight even in deep twilight, when the Sun is quite far below the horizon.
- Low-level, backlit clouds can have a pretty, glowing outline as sunlight filters through the thinner regions. Sunlight can also travel unimpeded through holes or gaps in the clouds, lighting up the air closer to us and creating bright streamers. These rays of light are known formally as **crepuscular rays** and informally as “Buddha’s rays” or “fingers of God.”
- Crepuscular rays seem to fan out from the Sun, but this is just a perspective effect. Light rays from the Sun are actually nearly parallel because of the Sun’s great distance from Earth, but they appear to diverge, just as parallel railroad tracks do.

The Sun Low on The Horizon

- When the Sun or Moon appears to be just starting to touch the horizon, it is actually already below the horizon by an amount roughly equal to its diameter.
- In the tropics to mid-latitudes, this makes the day last about 4 to 6 minutes longer than it otherwise would, depending on the **latitude** and **season**. At the equator, the day is almost exactly 4 minutes longer throughout the year.
- The reason for this is that the Sun’s rays are significantly refracted when they go through Earth’s atmosphere. They curve toward us and enter our eyes at a steeper angle than would have been the case without the atmosphere. This makes it appear as though the Sun is higher up in the sky, because our eyes only know the direction from which the light rays entered, not the fact that they curved through the atmosphere.

- The vertically flattened appearance of the very low Sun occurs because the amount of refraction for the bottom part of the Sun is larger than for the top. The bottom rays have gone through a thicker part of the atmosphere than the top rays, and the bottom part effectively gets “lifted” more than the top, making the Sun look squashed.

The Green Flash

- Just at the moment when the setting Sun is disappearing, you can sometimes see what’s called the **green flash**.
- The green flash results from the fact that the atmosphere spreads the Sun out into its component colors. The physical effect is just like that of a glass prism or a water droplet but much smaller in size.
- When the Sun appears just above the horizon, its light has actually been spread out into a tiny rainbow, with the blue portion higher than the green and the green higher than the red. The blue from the top part gets scattered and absorbed by the atmosphere, so we don’t see it.
- Generally, the shortest wavelength that survives its flight through the atmosphere is green, and that’s the top part of the Sun that we see.
- The green part of the Sun is visible for just a tiny fraction of a second, but the real green flash observed from Earth can last a few seconds. The explanation for this can be found in **mirages**. They distort the image of the Sun and can make the top part of it appear above the horizon for a longer time interval.
- Inferior mirages form when there’s a layer of hot, low-density air near the ground, such as above the black asphalt of a road. Incoming rays of light from the sky bend toward the higher, denser air entering the eye at a shallow angle. We then see an image of the sky straight out near the ground.

- Superior mirages form when there's a layer of cool, dense air below hotter, less dense air. Incoming rays of light from an object bend toward the lower, denser air, entering the eye at a steeper angle and appearing higher up. But the bottom rays bend more than the top ones, so those rays come into the eye even more steeply, and the object appears inverted.
- If the sky is clear and free of particulate matter, you can sometimes even see a blue flash because the blue rays aren't completely filtered out. This occurs more often at sunrise than sunset.
- Look for a green flash when the Sun is whitish-yellow because that means that the green color hasn't been strongly filtered out. It's also best to have a flat, true horizon, with no mountains, buildings, or trees.

Dramatic Sunsets

- Long, dramatic sunsets occur when the Sun sets at a shallow angle relative to the horizon. This also increases the duration of the sunset itself—the time during which part of the Sun is above the horizon and part is below.
- Such sunsets occur at high latitudes and near the summer solstice. To understand why, let's consider the time and position of the setting Sun.
- Day and night are a consequence of Earth's rotation, of course, and the lengths of daytime and nighttime depend on Earth's orientation relative to the Sun, which changes with time.
- Around June 22, Earth's Northern Hemisphere is tilted the maximum amount toward the Sun; this is the beginning of summer. The Sun is north of the celestial equator, so as Earth rotates, the Sun remains above the horizon for a long time if you're well north of the equator. Conversely, it's the beginning of winter in the southern latitudes, which experience less than 12 hours of daylight.

- On the autumnal **equinox** (September 22) and the vernal equinox (March 22), the Sun is on the celestial equator, and daytime lasts about 12 hours nearly everywhere.
- In December, Earth's Southern Hemisphere is tilted toward the Sun, so in the south, there is more than 12 hours of daylight, while the Northern Hemisphere has shorter days.
- On the Antarctic Circle, at 66.5 degrees south latitude, the Sun doesn't set at all on December 22. At the South Pole itself, the Sun is continuously above the horizon for about half a year!
- On the day of the equinox at the South Pole, the Sun should be right on the horizon, but it actually appears a little above the horizon because of atmospheric refraction. An observer at Earth's North Pole would also see the Sun above the horizon at this moment for the same reason.
- The duration of sunrise or sunset is also affected by latitude and season. In the tropics, the Sun sets almost vertically, but at high latitudes, it sets along a shallower angle relative to the horizon. The angle of the Sun approaching the horizon is also shallower in the summer than it is in the winter, thereby extending the duration of sunset in the summer relative to winter.
- As seen from the poles, by the way, sunset lasts about two-thirds of a day, and even the final stages may take almost an hour. That means that you could, in principle, have a green flash that lasts an hour!

Important Terms

alpenglow: Highly filtered sunlight (typically yellow, orange, or pink in color) seen shortly before sunset or after sunrise, reflecting off mountains. It can be especially beautiful when the mountains are covered with snow or glaciers.

antitwilight arch: The band of pinkish light in the east shortly after sunset or in the west shortly before sunrise. Produced by air that is still illuminated by direct but highly filtered sunlight. Also known as the Belt of Venus.

crepuscular rays: Beams of light shining through gaps in clouds, usually best seen near sunset or sunrise. Also informally known as Buddha's rays, fingers of God, or Sun rays. If seen in the direction opposite the Sun, they are sometimes called anticrepuscular rays.

equinox: One of two points of intersection between the ecliptic and the celestial equator or the time of the year when the Sun is at this position.

green flash: A subtle green glow sometimes visible in very clear skies just as the last part of the Sun is setting (or the first part is rising). Caused by atmospheric refraction and mirages.

latitude: For a given point on a planet, the number of degrees north or south of the equator, with the equator being 0 degrees and the poles being 90 degrees.

mirage: An image of an object, often but not always inverted, formed by light passing through layers of air having different temperatures and densities. An *inferior mirage* forms when there is a layer of hot, low-density air below cooler, denser air. A *superior mirage* forms when there is a layer of cool, dense air below hotter, less dense air.

nacreous clouds: Polar stratospheric clouds that form during polar winters at altitudes of about 10 to 16 miles. They have an iridescent color that resembles mother of pearl.

noctilucent clouds: High-altitude clouds, typically in the mesosphere at an altitude of about 50 miles, that can reflect sunlight even in deep twilight, when the Sun is quite far below the horizon.

purple light: A diffuse purple glow that is sometimes visible above the twilight arch. Produced by a combination of blue light Rayleigh-scattered by relatively low parts of the atmosphere and scattering by dust particles in the stratosphere. Tends to occur most frequently after volcanic eruptions.

seasons: Winter, spring, summer, and fall (or autumn). Caused by the fact that Earth's axis of rotation is tilted by 23.5 degrees relative to its axis of revolution around the Sun, making the Sun's path higher in the sky during summer and lower in the sky during winter.

twilight arch: A bright, colorful glow in the western sky near or shortly after sunset or in the eastern sky near or shortly before sunrise.

Suggested Reading

Lynch and Livingston, *Color and Light in Nature*.

Minnaert, *Light and Color in the Outdoors*.

Naylor, *Out of the Blue*.

Questions to Consider

1. If air molecules scattered red and orange light more than blue and violet light, what would be the typical colors of clouds near the times of sunrise and sunset?
2. Just after sunset or before sunrise, why isn't the Earth's shadow on the atmosphere completely dark?
3. Try to see the green flash at sunrise. You will need to look at the Sun just as it's rising, because the effect lasts only a short time. You might need to try on several consecutive mornings, so that you'll know exactly where to look. If the sky is very clear, you might even see a brief blue flash.
4. Note the exact times of sunrise and sunset for a few weeks surrounding the solstices, either by measuring them yourself or by consulting tables available online. Does the day of latest sunset correspond to the day of earliest sunrise near the summer solstice? If not, what do you think is the explanation? Similarly, does the day of earliest sunset correspond to the day of latest sunrise near the winter solstice?

Bright Stars, Constellations, and the Zodiac

Lecture 6

In the last lecture, we discussed the colors of sunrise and sunset and various phenomena associated with the rising and setting Sun. In this lecture, we'll move into the night, the domain of darkness punctuated by stars. We'll explore some of the most well-known constellations, learn some tips for orienting yourself in the night sky, and find out when and where you can see the brightest stars.

Evening Twilight

- Evening **twilight** (dusk) or morning twilight (dawn) occurs when the Sun is fully below the horizon but still shines on visible parts of the atmosphere.
- Civil twilight is the interval between sunset and when the geometric center of the Sun is 6 degrees below the horizon. Nautical twilight is the time when the Sun is between 6 and 12 degrees below the horizon. Astronomical twilight occurs when the Sun is between 12 and 18 degrees below the horizon.
- The end of civil twilight is often said to be about 30 minutes or so after sunset, but the actual duration depends on the observer's latitude and the time of year.
- In the tropics, the Sun sets almost vertically, and the transition between day and night takes only a short time. At high latitudes, the Sun sets along a path that is much less vertical; it moves along a shallower angle relative to the horizon, so twilight lasts longer.
- The durations of both sunset and twilight are also seasonal, and seasonal effects are greatest far from the equator.

The Appearance of the Stars

- Astronomers use the term apparent **magnitude** to quantify the apparent visual brightness of a star. A first-magnitude star is 100 times brighter than a sixth-magnitude star.
- Sirius, the brightest star in the evening sky in the winter, has a magnitude of -1.4 . In the hunter Orion, Rigel is 0.12 , Betelgeuse is roughly 0.5 , and the three belt stars are about magnitude 2 .
- Bright stars are not necessarily physically bigger than faint stars, but they look bigger to the eye and in photographs due to an effect called **irradiation**. Light hitting the eye's retina or a photographic emulsion is scattered away from where the imaged was focused, stimulating a larger patch of retinal cells and making the light source appear larger.
- The starlike shape of a star is caused by the fact that, at night, the pupil dilates to gather more light, and some of the light enters the lens near its distorted outer edges, producing spikes. If we had perfect lenses in our eyes, stars would look like tiny circles.
- In the case of photos made with a **reflecting telescope**, the spikes from stars are the diffraction pattern formed when light from a point source bends around the rods that support the secondary mirror.

Constellations

- **Constellations** are specific patterns or groups of stars. In most cases, the stars in a given constellation are at very different physical distances from us, aren't physically bound to each other, and did not form together.
- Some patterns of stars are easily recognized but are not, strictly speaking, constellations. These are called **asterisms**. The Big Dipper, for example, is an asterism within Ursa Major, the Great Bear.

- Though stars move relative to each other in our Milky Way galaxy, these motions are so slow relative to their great distances that the shapes of star patterns don't change perceptibly over our lifetimes.

Finding Your Way around the Sky

- Tools for finding your way around the sky include a star atlas, a device called a **planisphere**, and some computer and smartphone applications. The constellations are also useful for orienting yourself in the sky.
- If you live around 40 degrees north latitude, such as in New York City, Denver, or Reno, then Polaris, the North Star, will be 40 degrees above the horizon. The bowl of the Big Dipper and part of the handle will always be above the horizon, though just barely at certain times.
- Another way to orient yourself is to find Cassiopeia, which will be highest in the sky at midnight in early October and in the evening sky in mid-December.
- At midnight in late June or in the evening in August, both the Big Dipper and Cassiopeia will be up, straddling Polaris to the left and right. If you have a fairly dark sky and you see most of the Little Dipper pointing up and to the left, you'll also be able to see the stars of Draco the Dragon.

Zodiacal Constellations

- The other planets in our Solar System can be found amid the zodiacal constellations. These are also the constellations through which the Sun appears to move as Earth orbits it. The precise path that the Sun follows is called the ecliptic.
- The motions of planets don't exactly follow the ecliptic because their orbital planes are tilted slightly relative to ours by different

amounts. Thus, the planets are found in a slightly broader swath of the sky, the **zodiac**, centered on the ecliptic.

- There are 12 official zodiacal constellations, even though the Sun and planets also spend time in Ophiuchus the Serpent Bearer.
- The zodiacal constellations are crucial to **astrology**. The traditional horoscope is divided into 12 signs of equal size, 30 degrees across, but these are only symbolic of their associated constellations, whose sizes actually span a great range.
- Many of the zodiacal constellations are not very prominent in the sky. In fact, only five of them have a star brighter than magnitude 1.5. You can't see all of the constellations at a given time of night or a given time of the year. Indeed, parts of the sky are never visible from a given point on Earth, unless you're near the equator.

Your Location and What You See in the Sky

- As mentioned in Lecture 1, the stars are extremely far away and appear to be “glued” to a bowl-shaped dome around us—the celestial sphere. The north and south **celestial poles** are where an extension of Earth's rotation axis intersects the celestial sphere. The celestial equator is Earth's equator projected outward onto the celestial sphere.
- If you have a clear, flat horizon, at any given moment of time, you can see half of the celestial sphere because the stars are so far away compared



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Orion has some of the brightest stars in the Northern Hemisphere winter sky.

with Earth's size. You wouldn't see half of the celestial sphere at a given time if that sphere were closer.

- As Earth rotates around its axis, the stars rise in the east, move across the sky, and set in the west, just as the Sun does. The celestial sphere appears to rotate around us, although of course, it is Earth that is rotating.
- The altitude of Polaris above the horizon is equal to your latitude on Earth. If you're at Earth's North Pole, Polaris is straight overhead, but when viewed from Earth's equator, it's on the horizon.
- **Circumpolar stars** are those that are visible above the horizon all night and would be visible during the day if the sky were dark; they never rise or set because they're fairly close to the celestial pole. If you were at Earth's North Pole, stars would seem to circle around you, maintaining the same altitude above the horizon, neither rising nor setting.
- The zenith coincides with the north celestial pole, and the celestial equator is on the horizon. The south celestial pole is directly below you, far below the horizon. Indeed, you don't see any of the celestial Southern Hemisphere, because it's always below the horizon.
- If you were standing on the equator, the stars would rise straight up from the eastern horizon, arc across the sky, and set straight down in the west.
- As viewed from Earth's equator, no parts of the sky are circumpolar. The celestial poles themselves are at the equator due north and due south. Over the course of the 24-hour day/night cycle, you would see the entire celestial sphere if you were on the equator, but only about half of it at a given time of the night.
- At an intermediate latitude on Earth, say, 40 degrees north, stars rise at an angle relative to the eastern horizon, and they set at an angle

in the west. Thus, our view of the night sky depends on where we are on the spherical Earth and on the time of night we're viewing.

- Yet another factor determining what you see in the sky is the month because the direction face by Earth's night side continually changes.
- Suppose you're near Earth's equator at midnight in December. You'll see Orion overhead, because the zenith is in the direction of Orion. But by March, Earth will have moved in its orbit around the Sun, and at midnight, the zenith is in the direction of Virgo.
- The combination of Earth's rotation and its orbit around the Sun means that a given constellation viewed near the equator rises or sets about 2 hours earlier in successive months.

How and When to Find the Brightest Stars

- In the early evenings of April through September, if you follow the curve of the Big Dipper's handle outward by nearly twice its length, you'll come to the bright reddish-orange star Arcturus. At a magnitude of -0.04 , it's the brightest star north of the celestial equator and the fourth brightest in the whole sky.
- If you continue the arc of Arcturus by a similar distance, you will reach the first-magnitude star Spica in Virgo. Look for it in August or earlier.
- In the early evenings of spring, Spica is a good jumping off point to some other zodiacal constellations having at least one bright star. Immediately west of Virgo is Leo the Lion, with Regulus shining at magnitude 1.35. Further west, the eye of Taurus the Bull is the first-magnitude star Aldebaran, an even larger **red giant** than Arcturus.
- To the east of Virgo is Libra, then Scorpius, which has the reddish first-magnitude Antares as its heart. An even larger red **supergiant** is the reddish star Betelgeuse, which is about 1100 times the Sun's diameter.

- Bluish-white Rigel, in the right foot of Orion, is the seventh brightest star, at magnitude 0.12. Overall, Orion is the brightest constellation in the sky; it is most visible in the early evening in December through April.
- Orion's belt points up roughly toward Aldebaran, and continuing along that same line, you reach the Pleiades, or the Seven Sisters.
- To the upper left of Aldebaran and the Seven Sisters is the yellowish star Capella, the sixth brightest star in the night sky and the third brightest in the Northern Hemisphere.
- Extending Orion's belt down to the southeast, we come to Sirius, the brightest star in the sky, at magnitude -1.4 . Nearby is Procyon, in the constellation Canis Minor, shining at magnitude 0.34, the eighth brightest star in the sky. Betelgeuse, Sirius, and Procyon form what is sometimes called the Winter Triangle.
- The Summer Triangle consists of Vega, Altair, and Deneb. Vega is the fifth brightest star in the sky and the second brightest in the Northern Hemisphere. It's in the constellation Lyra the Harp.
- If you find yourself near the equator or in the Southern Hemisphere around March through July, be sure to look for the Southern Cross. To the east of it are the bright stars Alpha and Beta Centauri.
- Many of the bright stars in the sky twinkle. As we know, air bends, or refracts, starlight. Due to atmospheric turbulence, this refraction varies with time, so the amount of light hitting the eye varies, and this causes the **twinkling** effect.
- Stars closer to the horizon tend to twinkle more than those higher up because there's more air and turbulence closer to the horizon. Really bright stars, such as Sirius, can even change color as they twinkle.

Important Terms

asterism: An easily recognizable grouping of stars that is not itself a full constellation but is part of one or more constellations. The Big Dipper is one example; it is part of Ursa Major, the Great Bear.

astrology: The non-scientific belief that the positions of the Sun and various planets at the time of birth significantly affect one's life and personality. There is no significant evidence that astrology is correct and no physical mechanism or explanation for the alleged effects.

celestial pole: The projection of the Earth's North or South Pole onto the celestial sphere. The sky rotates around the celestial poles from east to west.

circumpolar star: As seen from a given location, a star that circles the celestial pole and never sets below the horizon.

irradiation: An effect in which the image of a star or other point-like source of light appears larger than expected when viewed by the human eye or in a photograph; the well-focused light is scattered, spreading out and affecting neighboring regions.

magnitude: A logarithmic measure of apparent brightness; a difference of 5 magnitudes corresponds to a brightness ratio of 100. Typical very bright stars have mag 1; typical faint naked-eye stars (in dark skies) have mag 6.

planisphere: A simple device that shows the stars and constellations that are visible from a given latitude or range of latitudes as a function of month and time of night.

red giant: The evolutionary phase following the main sequence of a relatively low-mass star, such as the Sun; the star grows in size and luminosity but has a cooler surface.

reflecting telescope: Telescope that uses a mirror instead of a lens to collect light; unlike the refracting telescope, it brings all colors into focus together.

supergiant: The evolutionary phase following the main sequence of a massive star; the star becomes more luminous and larger. If its size increases by a very large factor, it becomes cool (red).

twilight: The time after sunset (or before sunrise) when the sky is not fully dark. During civil, nautical, and astronomical twilight, the Sun is (respectively) 0 to 6 degrees, 6 to 12 degrees, and 12 to 18 degrees below the horizon.

twinkling: Rapid changes in the apparent brightness of a star; caused by light passing through turbulent layers in Earth's atmosphere having different densities and temperatures.

zodiac: The band of constellations through which the Sun moves during the course of a year. There are 12 classical zodiacal constellations; however, taking into account the formal constellation boundaries, Ophiuchus could be considered the 13th zodiacal constellation.

Suggested Reading

Chandler, *The Night Sky Planisphere*.

Dickinson, *Nightwatch*.

Edmund Scientific: Edmund Mag 5 Star Atlas.

Levy: *David Levy's Guide to the Night Sky*.

Naylor, *Out of the Blue*.

Pasachoff, *A Field Guide to the Stars and Planets*.

Pasachoff and Filippenko. *The Cosmos*.

Rey, *Find the Constellations*.

Rey, *The Stars*.

Ridpath, *Norton's Star Atlas*.

Tirion, *The Cambridge Star Atlas*.

Questions to Consider

1. If Star Frodo has an apparent magnitude of 8, and Star Bilbo has an apparent magnitude of 2, then roughly how bright is Bilbo relative to Frodo? (a) 250 (b) 100 (c) 6 (d) 4 (e) $\frac{1}{4}$.
2. Where on Earth would you have to be, to see the south celestial pole directly overhead? Would you ever be able to see the great Andromeda galaxy from this location, during your lifetime? (Note: The Andromeda galaxy passes nearly overhead during autumn nights for an observer at mid-northern latitudes.) At what location on Earth is the south celestial pole on the horizon?
3. Consult star charts or a planisphere, and learn to recognize some constellations and asterisms. After you know them well, are you able to look at the relevant parts of the sky and not immediately see these patterns?
4. Suppose that on September 1 at 10:00 p.m. you look toward the western horizon and see the bright star Antares setting. At roughly what time will Antares set 1 month later, on October 1, as seen from the same location? (Note: Antares is near the celestial equator, and let's assume you are near Earth's equator.)

Viewing the Planets and Their Motions

Lecture 7

In the last lecture, we discussed the celestial sphere and explored the stars at night, but some of the apparent stars seen in the sky are actually planets in our Solar System orbiting the Sun. In this lecture, we'll tour the inner and outer planets and learn how the transits of planets may help us find a world that could support life elsewhere in our Galaxy.

The Wandering of the Planets

- Planets gradually wander among the backdrop of so-called fixed stars in the constellations.
- Because the positions of the planets change with time, they can be a bit tricky to find. Also, to the unaided eye, planets closely resemble stars. Knowing the star patterns of the constellations can help you tell when one of the “stars” looks out of place. Often, the culprit is a planet.
- If you suspect that you've located a planet, you can verify your find by consulting a **star chart**, a planisphere, or online tables of the locations of planets at different times.
- Your suspected planet should change its position among the stars over the course of a few days or a few weeks or months. Take pictures on successive evenings to see if you can identify movement.
- Another good rule of thumb for distinguishing planets is the following: If it twinkles less than other stars of similar brightness that are at roughly the same altitude above the horizon, then it is likely to be a planet. The randomly twinkling points of light that make up a planet's disk tend to average out, but when the air is very turbulent, even planets will twinkle.

- Another tip when looking for planets is that some of them can be much brighter than stars. In fact, the first “star” that you see at night is frequently Venus, which shines at a magnitude of around -4 .
- If you see a star that is less than a degree or two above the horizon, it is likely to be a planet, because no stars are bright enough to be visible with the naked eye near the horizon, where the atmosphere dims their light significantly.

Viewing the Inner Planets

- The visibility of a planet at night depends a great deal on whether the planet is inside or outside Earth’s orbit. The inner planets always appear relatively close to the Sun, while the outer planets can be far away from it.
- Mercury, for example, is quite difficult to see because from our position on Earth, it always appears close to the Sun. Mercury is too faint to see when the Sun is up, and it sets shortly after sunset or rises shortly before sunrise. Even with a clear, obstacle-free horizon, Mercury can never be seen around midnight, because it is never opposite the direction of the Sun.
- Mercury is usually a bit above the horizon, within the bright twilight arch, and its light is greatly attenuated by the atmosphere because it is so low in the sky. Although its magnitude varies between 2.7 and -1.4 , it is actually very difficult to see when fainter than magnitude 0.
- To maximize your chances of seeing Mercury, you have to wait until it reaches a large angular separation from the Sun. In the evening, around the time of the vernal equinox, the ecliptic inclines more steeply toward the horizon, and Mercury will appear higher in the sky above the Sun.
- Like Mercury, Venus is an inner planet, but it is much easier to see. In fact, at a magnitude of -4 , it is the brightest permanent object in

the sky after the Sun and the Moon. Venus gets as far away from the Sun as about 46 degrees, so it is visible for up to a few hours after sunset in the west or before sunrise in the east.

Viewing the Outer Planets

- The outer planets are up in the night sky the longest at what is called **opposition**, when the Sun and the planet are on opposite sides of Earth and the planet is at its closest to Earth. At opposition, these planets rise in the east around sunset, are highest in the sky around midnight, and set in the west around sunrise.
- It is usually easier to see the outer planets one to three months after opposition, when the part of the sky in which they are located rises earlier in the night because Earth has moved part way around the Sun. They are already pretty high up in the east during the evening, and they set a few hours after midnight.
- The farther a planet is from opposition, the less time it is visible in the night sky. When the planet is in a direction that is close to the Sun, it might be visible for just 1–2 hours after sunset or before sunrise.
- When the outer planet is in the same direction as the Sun and behind it, it is said to be in **conjunction** with the Sun and is not visible at all. Usually, it is not directly blocked by the Sun, since Earth's orbital plane is not exactly the same as that of the other planets, but it will still be lost in the Sun's glare during the day.

Retrograde Motion

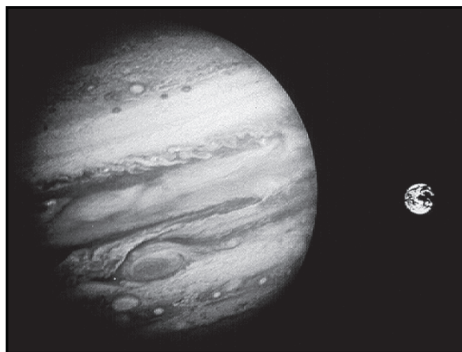
- The phenomenon of **retrograde motion** is quite obvious for the outer planets in opposition. This occurs when a planet seems to drift slowly among the stars from east to west, rather than the normal **prograde** direction of west to east.

- As a result of Earth's rotation around its axis, all the planets appear to rise in the east and set in the west once every 24 hours. If you compare the position of a planet with the stars over a few weeks, you will see that most of the time, the planet slowly drifts from west to east.
- However, for a period of time each year, the planets reverse this motion and drift from east to west. This retrograde motion is explained by a change in perspective when Earth passes Mars.
- At a certain location in the orbits of these two planets, Mars appears projected toward one part of the sky as seen from Earth. Earth is moving roughly perpendicular to Mars, and the position of Mars among the stars advances west to east.
- But when Mars is near opposition, Earth is passing it, and the position of Mars appears to drift backward. A bit later, Earth is again moving roughly perpendicular to Mars, so the apparent position of Mars drifts prograde again. The overall path is a loop or a backwards Z in the sky because the two orbital planes are tilted somewhat.
- Retrograde motion also occurs for the inner planets while passing Earth on the same side of the Sun. It is harder to detect, however, because the planets are close to the Sun and comparison stars are not so easily visible in the bright twilight sky.

A Tour of the Outer Planets

- Mars is the first planet beyond Earth's orbit, at a distance of 1.5 AU from the Sun. Because it moves quickly and goes through a great range in apparent brightness, Mars can be the hardest to find of the bright outer planets. At opposition, when Mars is closest to Earth and opposite the Sun's direction, it can be very bright, up to magnitude -2.7 . But because of the combined motion of Earth and Mars, opposition occurs only about every 2 years.

- Mercury, Venus, and Mars are called the terrestrial planets because they are relatively small and rocky, with an iron core. Their basic structure is like that of Earth. The planets Jupiter, Saturn, Uranus, and Neptune are the **Jovian planets**. They are much larger and consist mostly of gases, liquids, and in the case of Uranus and Neptune, ices.



Jupiter is the largest planet in the Solar System and is easily seen with the naked eye. Like all the planets, it moves through the zodiacal constellations.

- Jupiter is by far the largest and most massive planet in the Solar System. Its distance from Earth varies from about 4 AU at opposition to 6 AU at conjunction, and it is very bright in the sky, ranging from a magnitude of -2.5 at opposition to about -1.5 . Jupiter's orbital period is 12 years; on average, it moves eastward through one of the zodiacal constellations per year.
- Next largest among the Jovian planets is Saturn. Its rings consist of small bits of rubble, mostly ice from a disrupted moon or perhaps a moon that never fully formed. Saturn's apparent magnitude varies from about -0.3 to 1.3 , and its distance from Earth varies from about 9 AU at opposition to 11 AU at conjunction. Saturn's orbital period is nearly 30 years, so it moves eastward through one constellation roughly every 2.5 years.
- Uranus is the seventh planet from the Sun, at a distance of about 20 AU, and has a magnitude of 5.5 to 6 ; it is only barely visible to the unaided eye. Uranus takes 84 years to orbit the Sun, so on average, it remains in a given zodiacal constellation for about 7 years.

- Neptune, the eighth planet, is about 30 AU away in the Solar System's outer deep freeze. Neptune can be glimpsed through a good pair of binoculars if you know exactly where to look. Its magnitude is nearly constant at about 7.8. With an orbital period of about 165 years, Neptune spends nearly 14 years in a given zodiacal constellation.
- Pluto is no longer considered a genuine planet, because it lives in the **Kuiper Belt**, a swarm of similar bodies. At a magnitude of about 14 or 15, Pluto is far too faint to be seen with anything but a large telescope.
- A few **asteroids**, which are planetary fragments orbiting mostly between Mars and Jupiter, can be seen through binoculars. Vesta, the brightest asteroid, is sometimes barely visible to the naked eye on a dark, moonless night.

The Transits of Mercury and Venus

- Mercury and Venus sometimes pass directly between the Sun and Earth and appear to move across the Sun's disk.
- The **transit** of Venus can take many hours, depending on how close to the Sun's center the path goes. A transit does not occur every time Venus is between Earth and the Sun, because its orbital plane is tilted by about 3.4 degrees relative to Earth's plane; thus, it is usually somewhat above or below the Sun when it is in the right general direction.
- Transits of Venus always occur in pairs 8 years apart, followed by more than a century of no transits. The dates of the most recent transits of Venus are June 8, 2004, and June 5 or 6, 2012.
- Transits of Mercury are much more frequent than those of Venus, but they are still quite rare, typically occurring just once or twice a decade, because Mercury's orbital plane is tilted relative to Earth's.

- It is especially useful to look through a telescope (with the proper filter) if you are trying to view a transit of Mercury, which appears as just a tiny speck on the Sun's disk.
- Transits are now being used to find **exoplanets**, that is, planets orbiting around other stars. The basic idea is that some of the star's light is blocked by the transiting planet, making the star look fainter than normal for a short time; this happens with a well-defined period as the planet orbits the star.
- A space telescope called Kepler is now monitoring more than 150,000 stars to find such transits and has already found more than 1000 new exoplanet candidates.
- We now know that many stars have planets orbiting them—in some cases, at the proper distance for liquid water to exist on the surface. It may be that a near twin of Earth is among the candidate exoplanets already found by Kepler.

Important Terms

asteroid: A small body (smaller than a planet), in most cases consisting of rock or iron, that generally orbits the Sun between Mars and Jupiter.

conjunction: A planet is said to be in conjunction when it appears in the same (or nearly the same) direction as the Sun in the sky. Two planets are in conjunction when they are near each other in the sky (formally, they have the same celestial longitude).

exoplanet: A planet orbiting a star other than the Sun; also known as an extrasolar planet.

Jovian planets: In our solar system: Jupiter, Saturn, Uranus, and Neptune. Planets that are large compared with Earth and consist largely of gas and liquid, with solid cores. Also called giant planets.

Kuiper Belt: A reservoir of perhaps millions of solar-system objects orbiting the Sun generally outside the orbit of Neptune. Eris and Pluto are the two largest known Kuiper Belt objects, though some astronomers consider them to be planets.

opposition: A superior planet (that is, a planet outside Earth's orbit) is said to be in opposition when it is in the direction of the sky opposite that of the Sun. At that time, it is closer to Earth than at any other point in its orbit, and it's highest in the sky around midnight.

prograde motion: The apparent motion of the planets when they appear to gradually move from west to east among the stars; retrograde motion is the opposite direction.

retrograde motion: The apparent backward (east-to-west) motion among the stars that planets undergo for a short time each year.

star chart: A map of the sky showing the positions of stars and other objects, such as star clusters, nebulae, and galaxies. The boundaries of constellations are often marked. Also called a star atlas, especially if more details are shown.

transit: A transit occurs when a planet passes directly between Earth and either the Sun or another star. Also, a star is said to "transit" when it reaches its highest point in the sky, as seen from Earth's surface.

Suggested Reading

Chandler, *The Night Sky Planisphere*.

Dickinson, *Nightwatch*.

Edmund Scientific: *Edmund Mag 5 Star Atlas*.

Levy: *David Levy's Guide to the Night Sky*.

MacLachlin, *Galileo Galilei*.

Maor, *Venus in Transit*.

Naylor, *Out of the Blue*.

Pasachoff, *A Field Guide to the Stars and Planets*.

Pasachoff and Filippenko. *The Cosmos*.

Rey, *Find the Constellations*.

Rey, *The Stars*.

Ridpath, *Norton's Star Atlas*.

Tirion, *The Cambridge Star Atlas*.

Questions to Consider

1. Why do you think that Galileo's observation that Venus goes through a full set of phases, like the Moon, was incompatible with the geocentric (Earth-centered) model of the Solar System, in which the Sun and all planets go around the stationary Earth?
2. Try to detect the prograde and retrograde motions of Mars yourself. Over the course of several months, make at least a dozen naked-eye observations of the position of Mars relative to stars near it in the sky. (Draw diagrams showing the relative positions of Mars and various stars, or take photographs.) Try to start at least two months before opposition and end at least two months after opposition.
3. Try to detect Venus during the day with your naked eye. The easiest way to do this is by noticing it at dawn in the eastern sky, when it is very obvious, and keeping track of it after the Sun rises.
4. Find Jupiter or Saturn in the sky, and compare their naked-eye appearance with that of a comparably bright star having roughly the same altitude above the horizon. Does the planet twinkle less than the star?

The Moon, Phases, and Lunar Eclipses

Lecture 8

The Moon is easily the most viewed object in the sky, even more so than the Sun because it is not too bright to look at directly. Although looking at the full Moon has always been a favorite activity on romantic evenings, tracking its phases presents even more possibilities for skywatching. This lecture looks at these phases in detail, explains why the Moon looks so large near the horizon, and discusses lunar eclipses.

Our Nearest Celestial Neighbor

- The Moon is about 240,000 miles away from Earth, and we can get nice views of it with the unaided eye or through binoculars. Among its more obvious features are large **craters** and dark regions called the maria, or seas. These are lava flows that covered impact craters and solidified 3 to 4 billion years ago.
- Because the Sun shines on the full Moon from directly above, no shadows are created, and it can be difficult to see details on its surface. It is better to look at the Moon when it appears roughly half lit from our perspective.
- To a good first approximation, we always see the same face of the Moon regardless of its phase because the Moon rotates around its axis at the same rate that it orbits Earth.



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Details on a full Moon are actually harder to observe than on a quarter Moon.

- The Moon once rotated faster than it orbited Earth, but a gravitational interaction with Earth, the so-called **tidal force**, slowed it down until it became locked into synchronous rotation.
- Despite appearances, we do not see exactly the same face of the Moon at all times. The fact that the Moon's orbit is elliptical rather than circular and that its orbital speed varies with time (but its rotation around its axis does not) results in an effect called **libration**, an apparent wobbling motion.

The Lunar Phases

- The phases of the Moon are as follows: new, **waxing** crescent, first quarter, waxing gibbous, full, **waning** gibbous, third quarter, waning crescent, and new again. The full cycle takes a total of 29.5 days.
- The key to understanding the lunar phases is to know that the Moon shines only by reflecting sunlight. The hemisphere that is facing the Sun is lit up and the one that is not is dark.
- The portion of the lit-up hemisphere we see depends on the relative positions of the Sun, the Moon, and Earth, and this geometric relationship changes over the course of a lunar orbit. If we track the orbit of the Moon in relation to the Sun, we can see that what is observed on Earth is only the hemisphere that is facing us, not necessarily the entire lit-up hemisphere.
- There is no perpetually dark side of the Moon. All sides are eventually lit up, but there is a perpetually far side of the Moon, and we do not see it from Earth even when it is lit up.
- You can determine the best time to view the various phases of the Moon by figuring out when it will be above the horizon from your position on Earth. For example, the waxing crescent Moon is not visible between the hours of about 9:00 p.m. and 9:00 a.m. because it's simply not up in the sky, but it can be seen mostly during the day.

- The first-quarter Moon rises around noon, is highest in the sky at sunset, and sets about midnight. Similarly, the full Moon rises at sunset and sets at sunrise. The third-quarter Moon rises around midnight, is highest in the sky at sunrise, and sets at about noon.
- If you view the crescent Moon a few days after the new Moon in a relatively dark sky, you will see the dark side faintly lit up. This phenomenon is called **earthshine**. When we see the crescent Moon, Earth looks **gibbous** from the Moon's vantage point. The Earth reflects sunlight toward the Moon, and the Moon then reflects some of it back toward Earth. Thus, the dark part of the hemisphere facing us looks faintly lit up.
- The amount by which the brightness of the Moon increases as it waxes tells us about the lunar surface. The full Moon is about 12 times brighter than the quarter Moon even though the lit-up area is only twice as large. That's because there are no shadows when we view the full Moon, so each part of the surface adds to the brightness. In contrast, the quarter phase has lots of shadows.
- This effect is enhanced by the Moon's rough, dust-covered surface. When light comes in to spaces between the dust particles at an angle, it bounces around and reemerges in random directions. At full Moon, light goes down to the bottom of the holes between dust particles and reflects straight back out in our direction, making the surface look bright.

The Position of the Moon

- The Moon appears to rotate as it moves across the sky on a given day or night. This effect is caused by the fact that we are viewing the Moon from a spherical spinning Earth.
- Each day or night, as seen from a given point on Earth, the Moon rises in the east and sets in the west, following an arc parallel to the celestial equator. The Moon is somewhere on or near the ecliptic in the sky because the orbital planes of the Moon and Earth are

nearly the same. Because of its orbital motion around Earth, the Moon will appear to move eastward among the stars of the zodiacal constellations by about 12 degrees each day.

- The Moon will rise and set, on average, 50 minutes later each day. Like the Sun, the Moon's maximum height above the horizon varies widely over the year. It gets high in the summer, low in the winter, and intermediate at the equinoxes.
- In the summer, the Northern Hemisphere of Earth is tilted toward the Sun, and the Sun looks high in the sky. At the same time, the crescent Moon is in the same general directions as the Sun, and it is high in the sky, as well.
- When the Moon is full, then it is in the part of the sky that is opposite the Sun and Earth's Northern Hemisphere is tilted away from it. It will look low in the sky during full Moon and high in the sky during new Moon.
- In winter in the Northern Hemisphere, the Sun looks low in the sky because Earth's Northern Hemisphere is tilted away from it. It is the same thing with the crescent Moon but just the opposite with the full Moon.
- The first-quarter Moon achieves its greatest height above the horizon in the spring, its lowest height in the autumn, and medium values in the summer and winter. Conversely, the third-quarter Moon is highest in the autumn, lowest in the spring, and intermediate in the summer and winter.

The Moon's Motion along the Ecliptic

- Another interesting thing to consider is the angle of the ecliptic relative to the horizon near the time of moonrise or moonset. Consider the waxing crescent Moon near sunset.

- In the spring, the ecliptic makes a steep angle relative to the horizon at sunset. The waxing crescent Moon looks like a slightly tilted, almost horizontal bowl relative to the horizon.
- In the summer or winter, the ecliptic makes a shallower angle relative to the horizon at sunset, and the crescent Moon looks more tilted. In the autumn, the ecliptic makes its shallowest angle at sunset, so the crescent Moon is really quite tilted.
- The so-called **harvest Moon** occurs in the autumn, when the full or nearly full Moon tends to rise just a short time later on a few consecutive evenings. The explanation for this also involves the angle of the ecliptic relative to the horizon.
- Recall that all celestial objects, including the Moon, follow paths that are parallel to the celestial equator. They rise upward in the east along these paths.
- Near the autumnal equinox, the ecliptic makes a shallow angle relative to the horizon. This means that on consecutive days, when the Moon moves along the ecliptic, it rises a little later each evening. It travels along a path parallel to the celestial equator, but it is a little bit more below the horizon along the ecliptic on consecutive nights.
- In the spring, the ecliptic makes a steep angle relative to the horizon, so the Moon's daily motion along the ecliptic puts it much farther below the horizon with each passing day, and it rises substantially later on consecutive evenings.

The Apparent Size of the Moon

- Most people have noticed that the Moon looks quite large near the horizon. This effect (the **Moon illusion**) is most pronounced when the Moon is full or nearly full.

- At its closest approach to Earth in its elliptical orbit, the Moon is actually about 12% closer than it is at its farthest. When it is closest to Earth, its apparent size in the sky is also 12% larger than when it is farthest away. But this is not the cause of the Moon illusion, in which the rising or setting Moon looks larger than when it is high in the sky the same night.



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- Although the Moon may appear larger when it is on or near the horizon, its angular size is actually a bit smaller in this position. The full Moon is about 1 Earth radius farther away when it is rising at sunset than when it is nearly overhead around midnight. This means that the Moon's angular size is actually a bit smaller when it is on the horizon compared to when it is high in the sky because it is farther away.
- When the Moon (or the Sun) is close to the horizon, it looks flattened. Its vertical size seems smaller due to differences in refraction of light between its top and bottom.

Lunar eclipses occur when the Moon enters Earth's shadow. Partial or total lunar eclipses are visible a few times per year.

Lunar Eclipses

- Because the Moon's and Earth's orbital planes are tipped by about 5 degrees, the full Moon usually misses Earth's shadow. A few times per year, however, the full Moon is near the location where the Moon crosses Earth's orbital plane. The Sun, Earth, and the Moon are nearly in a straight line, so part or all of the Moon can fall in Earth's shadow (the **umbra**), creating a **lunar eclipse**.

- Usually, only part of the Moon is in the umbra, and we see only a partial lunar eclipse. The partial phase can last up to an hour or so.
- During an **eclipse**, most of the sunlight is blocked by the solid Earth, but some of it passes through Earth's atmosphere and is refracted toward the Moon. This light hits the Moon and is reflected back toward Earth, allowing us to see the Moon.
- In the process of passing through Earth's atmosphere, the violets, blues, and greens in this light tend to get scattered out of the line of sight by air molecules and dust particles, allowing mostly the yellow, orange, and red light to reach the Moon.
- From the Moon's point of view, during a lunar eclipse, a total **solar eclipse** is taking place, because the Sun is being blocked by Earth.
- Note that the edge of the shadow gets more sunlight than the central parts because the total amount of bending is less for the edge than for the center. Thus, the parts of the Moon closest to the edge are brighter than those in the center.
- You're much more likely to see a total lunar eclipse than a total solar eclipse, even though they occur with about the same regularity, because lunar eclipses are visible from the entire nighttime side of Earth. In fact, if you take into account Earth's rotation during roughly 1 hour of totality, at least some part of totality is visible from more than half of Earth's surface.

Important Terms

crater: A generally circular region on a moon or planet produced by the impact of an asteroid or meteoroid. There are also volcanic craters made by eruptions.

earthshine: Sunlight illuminating the Moon after having been reflected from Earth.

eclipse: The passage of one celestial body into the shadow of another or the obscuration of one celestial body by another body passing in front of it. From Earth, we see solar eclipses when the Moon passes in front of the Sun and lunar eclipses when the Moon goes into Earth's shadow.

gibbous: The phase of the Moon when it appears between half lit ("quarter Moon") and fully lit ("full Moon"). Can apply to the appearance of a planet, as well.

harvest moon: The full Moon near the autumnal equinox, when it rises a short time later on a few consecutive nights.

libration: The slight apparent wobbling of the Moon, despite the synchronous rotation, so that we see more than just half of its total surface area.

lunar eclipse: Occurs when the Moon partially and fully goes into Earth's shadow. During the penumbral phase, an observer on the Moon would see part of the Sun not blocked by Earth, but during the umbral phase, all of the photosphere is blocked (although some sunlight still bends through Earth's atmosphere and faintly illuminates the Moon).

Moon illusion: The apparently larger size of the Moon (generally gibbous or full) when it is near the horizon compared with when it is high in the sky. The effect is still not fully explained, but it may be in part a Ponzo illusion or related to the flattened appearance of the celestial sphere.

solar eclipse: A full or partial covering of the Sun's photosphere (visible surface) when the Moon is between Earth and the Sun. The partial phases must be viewed through a protective filter or by projection techniques, such as a pinhole camera.

tidal force: The difference between the gravitational force exerted by one body on the near and far sides of another body.

umbra: The dark part of the shadow of an object, from within which it appears that the Sun is fully blocked.

waning: Getting progressively smaller; specifically, the Moon is waning from full Moon to new Moon.

waxing: Getting progressively larger; specifically, the Moon is waxing from new Moon to full Moon.

Suggested Reading

Dickinson, *Nightwatch*.

Levy, *David Levy's Guide to the Night Sky*.

Long, *The Moon Book*.

Naylor, *Out of the Blue*.

Pasachoff, *A Field Guide to the Stars and Planets*.

Pasachoff and Filippenko. *The Cosmos*.

Ridpath, *Norton's Star Atlas*.

Ruhl and Seronik, *Atlas of the Moon*.

Questions to Consider

1. Suppose you see the Moon rise tonight at 8 p.m. Your friend will be visiting in 10 days, and you want to take her out to see the Moon rise when she visits. Roughly what time should you go outside in 10 days to impress your friend by catching moonrise? (a) 8 a.m. (b) noon (c) 4 p.m. (d) midnight (e) 4 a.m.
2. Try to detect the Moon's librations by drawing a picture (or taking a photograph) of the Moon on several nights over the course of a month, accurately showing the positions of a few maria or large craters relative to the Moon's edge (not the terminator). It is helpful to examine the Moon through binoculars, when determining relative positions.

3. To convince yourself that the Moon illusion is indeed an illusion, try photographing the Moon through a zoom lens when it is near the horizon, and also that same night when it's high in the sky. Compare the size of the Moon's image in the two photos, which were taken with the same telephoto setting.
4. What are the various factors that determine the duration of a total lunar eclipse, as well as the apparent brightness and color of different parts of the Moon during totality?

Satellites, Comets, and Meteors

Lecture 9

In the previous lecture, we discussed Earth's natural satellite, the Moon, which moves eastward against the background of fixed stars about 12 degrees per day. Humans have produced numerous artificial satellites that also orbit Earth and move across the sky, usually more rapidly than the Moon. In this lecture, we'll learn about the three main classes of artificial satellites and about other objects in the sky whose positions vary with time, including comets and meteors.

Artificial Satellites

- Artificial **satellites** are launched by rockets into orbits above most or all of Earth's atmosphere. *Sputnik 1*, launched by the Soviet Union on October 4, 1957, was the first such satellite.
- There are now thousands of satellites orbiting Earth, and they are used for all kinds of purposes in science, communications, weather, defense, and so on.
- A satellite can be seen as a point of light moving in a constant direction; it takes perhaps 5 to 10 minutes to cross the entire sky. Most of them look quite different from meteors, which zip through the sky in a matter of a few seconds or less.
- Only a few satellites are sufficiently large and nearby to be easily seen with the naked eye, but some are really quite obvious. For example, the International Space Station orbits at only about 200 miles above Earth.
- There are three main classes of artificial satellites based on how high they orbit. The ones in low Earth orbit, such as the Space Station, are just a few hundred miles above Earth's surface. The satellites in middle Earth orbit are typically at a height of about 3

Earth radii above the surface, while those in high Earth orbit are at least 5.5 Earth radii above the surface.

Satellites in Low Earth Orbit

- Satellites in low Earth orbit shine by reflecting sunlight, but usually, the daytime sky overwhelms their brightness, so they cannot be seen. At night, when they are usually in Earth's shadow, there is no sunlight to reflect, so satellites cannot be seen then either. The best time to see a satellite is in evening or morning twilight, generally within 1–2 hours after sunset or before sunrise.
- In addition to the Space Station, NASA's famous Hubble Space Telescope is another satellite that can be seen, although it is smaller than the Space Station and harder to spot. You can look online for Web sites that identify when and where different satellites can be viewed.
- Iridium flares are bright flashes caused by sunlight reflecting off antennas and solar panels on the so-called iridium satellites, a network of 66 active telecommunication satellites that have polar orbits around 500 miles above Earth. Iridium flares move quickly and can have magnitudes of -9 or -10 .

Satellites in Middle Earth Orbit

- Middle-Earth-orbit satellites are typically a few Earth radii above Earth's surface. Like low-Earth satellites, they also shine by reflecting sunlight. Some of them can be seen late at night if they are not in Earth's shadow. Being so far away, they are faint, and they cruise slowly across the sky.
- Most middle-Earth satellites shine at a fairly constant brightness, although some of them brighten and fade periodically. This indicates that they are rotating and one side is more reflective than the other.

- If you are out on a clear, dark, moonless night and your eyes become adapted to the dark, you can sometimes see several of these satellites with your unaided eyes in a span of just 15 minutes. If you follow one with your eyes or binoculars, you may actually see it fade away as it enters Earth's shadow and becomes invisible.



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Satellites in low and middle Earth orbit can sometimes be viewed unaided.

- Probably the best-known satellites in middle Earth orbit are those in the global positioning system (GPS), although they are too faint to see with the naked eye. The GPS is a network of 24 satellites, each of which has a 12-hour orbit.
- The **GPS satellites** have atomic clocks on them and transmit radio signals to receivers, such as one in your car. From the timing of the emitted and received signals from a group of these satellites, your car's position on Earth is uniquely determined.
- The clocks in the GPS satellites run slightly faster than clocks here on Earth because the satellite clocks are in a weaker gravitational field.

Satellites in High Earth Orbit

- The **geostationary satellites** are the best known and most important of the satellites in high Earth orbit. Each of these remains above a nearly constant spot on Earth because it orbits Earth at the same rate that Earth rotates.

- Although each satellite stays above a constant location, it is up high and sees a large fraction of Earth's facing hemisphere. These satellites are useful for communications and weather monitoring. Their orbits are close to the celestial equator, and they can usually be seen in the middle of the night because they are not in Earth's shadow and are able to reflect Earth's sunlight.
- Although the geostationary satellites are generally too faint to see with the naked eye, some of them are visible through a small telescope if you know exactly where to look.

Comets

- **Comets** appear as diffuse luminous patches in the sky, often with long tails. They move among the stars from night to night and are usually visible only over a few weeks or months.
- A comet is basically a dirty snowball or an icy dirt ball—a ball of rock, dust, and ice that comes in from the deep freeze of the outer Solar System. The ice consists of frozen water, ammonia, methane, carbon dioxide, and other molecules that evaporate away as the comet approaches the Sun because the comet gets heated.
- The heat of the Sun also releases dust and rocks in the comet because the icy “glue” that holds them together evaporates. The dust and gases get pushed by the pressure of sunlight and by the **solar wind**, which consists of high-speed charged particles. The dust particles from the comet reflect sunlight,



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A comet's tail always points away from the Sun, no matter its direction of travel.

causing a white curved tail. The ionized gases glow or fluoresce when they interact with the Sun's ultraviolet radiation, forming a straight bluish ion tail or gas tail.

- There is nothing actually burning in the tail of a comet. The dust and gas are simply scattered by sunlight or glow due to fluorescence and, thus, appear to be burning. Also, note that the tail always points generally away from the Sun. It is being pushed back by the pressure of sunlight and charged particles, but it does not always trail the comet.
- The nucleus of a comet may be a few miles to 20 or 25 miles across. It is difficult to see even a large nucleus from the ground because it reflects less than 5% of the incoming sunlight. Around the nucleus is the fuzzy coma of dust and evaporated gases, which is easily visible in a bright comet.
- Comets have two main types of tails, the straight ion tail and the somewhat curved dust tail. The curve of the dust tail is the result of the ejected gases gradually moving away from the nucleus and taking on a slower orbit that is farther from the Sun.
- The ion tail always points straight away from the Sun because the gas ions follow the magnetic field lines of the solar wind, which are fairly straight far from the Sun.
- Each year, there are usually some comets that are visible through binoculars or a small telescope. Their nuclei are only a few hundred yards across, but the coma grows to a much larger size. Again, you can consult the Internet to find out where and when to look.
- Some comets can suddenly brighten significantly when the nucleus heats up and ejects a large quantity of gas and dust, which then reflects sunlight.

- Periodic comets generally have orbital periods of a few years to a few hundred years. They have elliptical, highly eccentric orbits and spend most of their time far away from the Sun. When they come to the inner part of the Solar System, they zoom past the Sun very quickly.
- Most comets are not periodic. They visit the Sun only once or have orbital periods of many thousands of years, so we cannot anticipate their arrival.
- Some comets come so close to the Sun that they are called **Sun-grazing comets**. In fact, they sometimes plunge into the Sun without successfully grazing it.
- Comets sometimes break apart when they are near the Sun, allowing us to study their components.

Meteors and Meteor Showers

- **Meteors** appear as fast streaks of light in the sky. They are small pebbles or chunks of ice from the asteroid belt or comet debris. When they are wandering through the Solar System, they are called **meteoroids**.
- When meteoroids enter Earth's atmosphere at a height of around 60 or 70 miles, they compress and heat the surrounding air, causing it to glow brightly. In most cases, the meteoroid burns up before it reaches Earth.
- Most meteors are faint, but some are very bright. Those that are brighter than Venus (magnitude -4) are called **fireballs**. Exceptionally bright fireballs are called **bolides**, especially if they break up or explode while streaking through the atmosphere.
- **Sporadic meteors**, which come in from random directions, with no clear pattern, are best seen after midnight, when we are facing the direction in which Earth orbits the Sun.

- **Meteor showers** occur when Earth is passing through the orbit of an old, disintegrated comet or a younger comet that is shedding a good bit of debris. During such events, you might see a few dozen meteors per hour.
- Each year, there are 1–2 showers associated with a specific comet, depending on whether its orbital plane is tilted relative to Earth’s orbital plane. The showers are named after the constellations in which their radiants (apparent points of origin in the sky) are located.
- The best way to view a meteor shower is to find a dark location on the peak nights of the shower. The radiant must be above the horizon, and the higher the radiant is, the more meteors you are likely to see. If you look away from the radiant by 50 to 90 degrees, you may see fewer meteors, but their paths will be longer, streaking across the sky.

Important Terms

bolide: An exceptionally bright meteor. A very bright fireball is often called a bolide, especially if it breaks up into many pieces while streaking through the atmosphere.

comet: An interplanetary chunk of ice and rock (sometimes called a “dirty snowball” or an “icy dirtball”), usually in a very eccentric (elongated) orbit. Comets can partly evaporate (sublimate) when relatively near the Sun, forming a diffuse patch of light in the sky (a “coma” and sometimes a long “tail”) that consists of glowing ionized gas, as well as reflected sunlight.

fireball: An extremely bright meteor; also known as a bolide, if exceptionally bright.

geostationary satellite: Generally refers to an artificial satellite that orbits Earth above the equator at the same rate at which Earth rotates; the satellite remains above the same location on Earth at all times.

GPS satellite: An artificial satellite in mid-Earth orbit, used for the global positioning system (GPS).

meteor: The streak of light in the sky (“shooting star” or “falling star”) produced when an interplanetary rock enters Earth’s atmosphere and burns up as a result of air compression. If the rock reaches Earth’s surface, it is called a *meteorite*.

meteor shower: A larger than normal rate of meteors coming from a particular direction in the sky, typically several dozen per hour. Occurs when Earth goes through the orbit of a dead or disintegrating comet.

meteoroid: An interplanetary body smaller than an asteroid, perhaps up to a few tens of meters in diameter but typically larger than 0.1 mm.

satellite: An object orbiting another body; for example, the Moon is Earth’s natural satellite. Artificial satellites are generally in three main classes: low-Earth orbit (within a few hundred miles), middle-Earth orbit (a few Earth radii), and high-Earth orbit (often geostationary, at 5.5 Earth radii from Earth’s surface).

solar wind: A continuous stream of charged particles heading outward from the Sun’s corona; can vary with time owing to prominences, solar flares, and coronal mass ejections.

sporadic meteor: A meteor that is not associated with a known meteor shower.

Sun-grazing comet: A comet that comes very close to the Sun and, in some cases, plunges into the Sun.

Suggested Reading

Dickinson, *Nightwatch*.

Levy, *David Levy’s Guide to the Night Sky*.

Naylor, *Out of the Blue*.

Pasachoff, *A Field Guide to the Stars and Planets*.

Pasachoff and Filippenko. *The Cosmos*.

Questions to Consider

1. Calculate the approximate speed of a geostationary satellite orbiting above Earth's equator. Note that such satellites are about 5.5 Earth radii above Earth's surface, and that Earth's equatorial radius is 3960 miles.
2. Try photographing star trails, satellites, and meteors. Choose a dark location far from city lights, preferably at a time when the Moon is down. Set your camera on a tripod, point it up, make the lens opening wide (that is, set it to a low f-number, such as $f/2.8$), disable the flash unit, set the camera focus to infinity, and open the shutter (preferably with a cable release to minimize vibrations) for some period of time, typically 5 to 30 minutes. Be careful not to shine lights near the camera when the shutter is open. Your camera must have the option of taking a long exposure (normally the "bulb" setting); an "instamatic camera" won't work, and even some automatic single-lens-reflex (SLR) cameras don't have this option. Your best bet is a manual SLR.
3. Watch a meteor shower. Bundle up against the cold, bring a reclining lawn chair or sleeping bag if possible, and find as dark a site as you can with a wide-open view of the sky. Lie back, relax, and gaze up at the sky for at least an hour. Perhaps count how many meteors you see. Note any especially bright ones. Occasionally colors are visible in the streak of light, and a vapor trail can remain for a few seconds.
4. If periodic comets lose some of their material each time they pass by the Sun, and it takes only a few hundred orbits (on average) to completely destroy a comet, can you argue that there must be at least one reservoir of icy objects far from the Sun that is the source of new comets?

Observing Solar Activity and Earth's Auroras

Lecture 10

The Sun is familiar to all of us, of course, but there is much more to it than meets the eye. In this lecture, we'll see how charged particles from the Sun interact with Earth's magnetic field and atmosphere, producing what is known as "space weather" and generating the northern and southern lights. As we'll see, the most violent outbursts from the Sun also have the potential to disrupt communication satellites and lead to massive power outages here on Earth.

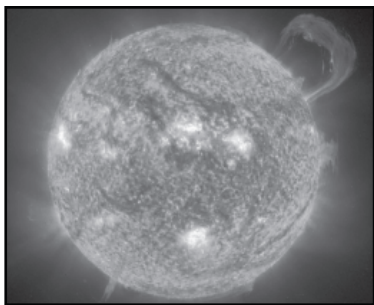
The Structure of the Sun

- The Sun's **photosphere**, from which the photons of light emerge, is generally referred to as its surface or disk. You can see some dark spots on it called **sunspots**.
- Surrounding the photosphere is a thin pink or reddish layer called the **chromosphere**, which is hotter than the photosphere.
- Around the chromosphere is the extremely hot corona, which flows out to form the solar wind of charged particles. Flares and coronal mass ejections are powerful outbursts from the Sun's surface that contribute to the solar wind. The solar wind eventually reaches Earth and produces **auroras**.

The Photosphere

- We can think of the photosphere, the visible surface of the Sun, as the lowest level of the Sun's atmosphere. It is about 1 million miles across, or about 109 times Earth's diameter. The photosphere's temperature is about 5800 kelvins on the absolute scale, or a little higher than 10,000 degrees Fahrenheit.

- The apparent surface of the Sun is well defined, with a sharp edge, but it is not a hard surface. Almost all of the Sun is ionized gas called **plasma**.
- The photosphere is where the Sun's gas becomes thin enough for the photons to escape into space. Below that, the light is trapped by the dense gas. In fact, after being created by nuclear reactions near the Sun's center, light takes about 100,000 years to actually reach the photosphere and escape.
- As mentioned throughout these lectures, it is essential to have a proper filter for looking at the Sun. **Shade 14 welder's glass** is highly recommended for viewing the Sun on a daily basis because it is inexpensive and unlikely to be scratched or damaged.
- The Sun looks darker near the edge than it does farther in. This phenomenon is called limb darkening. It occurs because near the edge or limb, we are seeing light coming from cooler, darker gas that is farther out from the Sun's center.
- Sunspots are relatively cool spots on the photosphere, and because they are cooler, they emit only a fraction of the energy of the surrounding gases and look dark by comparison.



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The Sun looks like a solid object, but it consists almost entirely of ionized gas called plasma.

- The Sun is permeated by a magnetic field, and sunspots are regions where this magnetic field is especially strong and tangled. That tangled magnetic field slows down the outward flow of charged particles in the hot plasma underneath. The gas near the surface cools down as it radiates, but it does not get easily replenished with hot gas from inside.

- Galileo and other early astronomers realized that the Sun is rotating by looking at sunspots crossing the visible disk of the Sun. Today, there are several spacecraft monitoring the Sun, and you can view their images and films online to monitor sunspots and the Sun's rotation.

The Chromosphere

- Right above the photosphere is a layer called the chromosphere. It is very thin, roughly the diameter of Earth, and quite colorful. The chromosphere is about twice as hot as the photosphere.
- The chromosphere looks red or pink because hot neutral hydrogen atoms glow with this color. These atoms collide with one another, releasing electrons to the third energy level; when electrons jump down to the second energy level, they emit this pinkish light. This electronic transition in hydrogen is known as **H-alpha**.
- The high temperature of the chromosphere is not yet fully understood, but it may partially result from mechanical heating by pressure waves and through energy released from magnetic fields near the Sun's surface.

The Corona

- The corona is the very tenuous outer atmosphere of the Sun that becomes much less dense the farther out it goes. It is fainter than the blue daytime sky, so you generally can see it only during a total solar eclipse, when the Moon blocks the Sun's disk and the sky darkens.
- The delicate structure of the corona is caused by charged particles in the plasma flowing along the magnetic field that exists around the Sun. The magnetic field is roughly radial, but it has many loops and kinks near the Sun's surface.

- The temperature of the corona is a few million degrees Fahrenheit. That means that the individual particles are moving around quickly in random directions. The density is so low that the total heat content is not very high and the corona is faint.
- Amazingly, if you were to immerse yourself in the corona, you would freeze to death. The particles in the corona are moving quickly, and they would hit you, transferring energy to you. But there are not many of these particles, so the rate of energy transfer is slow. Meanwhile, you would be radiating energy to the outside world at a faster rate, so you would cool down and, ultimately, freeze in this million-degree gas.
- The reason the corona is so incredibly hot is thought to involve magnetic energy. There is a great deal of energy stored in the Sun's magnetic field, and it is sometimes released, heating the gases.
- Because the corona is so hot, it is ionized. The atoms collide with one another at high speeds and strip off at least some of the electrons, resulting in free negatively charged electrons and positively charged ions.
- As it flows farther away from the Sun, the ionized corona gradually thins out and forms what is called the solar wind. This is a mass of electrons and positive ions streaming from the Sun through otherwise empty space; it can be thought of as the outer extension of the corona.

Outbursts from the Sun

- Solar prominences are eruptions of gas from the Sun's surface and chromosphere. A close-up view reveals their loopy structure. Some of these gases are ionized and flow along the loops of magnetic fields sticking out of the Sun's surface. The loops can last from minutes to days.

- Some prominences can be huge, expanding outward to roughly half of the Sun's radius.
- Although prominences can sometimes be quite large and powerful, most of the time, their total energy release is dwarfed by two other phenomena, **solar flares** and **coronal mass ejections**.
- Solar flares are extremely energetic eruptions from relatively small, localized regions on the Sun. Their temperature can approach 10 million degrees Fahrenheit.
- Flares tend to occur in regions of strong, tangled magnetic fields. A flare is produced by the release of magnetic energy. A process called magnetic reconnection occurs, destroying the magnetic fields and using their energy to accelerate charged particles to very high speeds.
- In a coronal mass ejection, a significant portion of the corona appears to shoot out of the Sun, spewing high-energy particles into space. These ejections tend to be spread out over a larger area than solar flares.
- The flood of charged particles ejected by flares and coronal mass ejections can sometimes have harmful effects on Earth and can be a definite hazard for astronauts. The surge of high-energy charged particles can disrupt the electronic circuit boards of communication satellites and produce geomagnetic storms that blow out power grids on Earth's surface.
- There is a growing interest among scientists and others in "space weather," the effects on Earth produced by sudden outbursts from the Sun.

The Solar Activity Cycle

- Sunspot activity seems to follow a cycle of roughly 11 years. Near sunspot minimum, there are few if any spots, sometimes for months at a time. Near sunspot maximum, many spots are seen on the Sun at a given time.

- Sunspots tend to form first at high latitudes, and then they form at lower latitudes closer to the equator as the cycle progresses.
- Flares, prominences, coronal mass ejections, and other forms of solar activity also follow the sunspot cycle.
- We can monitor how the Sun's magnetic field changes with time during the solar cycle. The shape of the corona is never the same during solar eclipses, but there are some broad patterns. Slightly before the solar maximum, the corona is quite complex but reasonably symmetric, with streamers going in many directions. Near the solar minimum, we see long streamers roughly centered on the Sun's equator.
- The cause of the solar activity cycle is not well understood. The Sun is a complex dynamo with a magnetic field threading through it and electric currents inside. Further, the polarity of the magnetic field flips roughly every 11 years.

Auroras

- The northern and southern lights (aurora borealis and aurora australis) are beautiful and quite harmless examples of the Sun-Earth connection.
- These phenomena are produced when the charged particles in the solar wind get trapped in Earth's magnetic field. They are not able to easily cross magnetic field lines, so they spiral around them. The particles are found mostly in a few regions called the **Van Allen belts**.
- The main Van Allen belts are far from Earth's surface in most places, but near the poles, they intersect Earth's thin atmosphere. There, the energetic particles collide with atoms and molecules, and part of their kinetic energy goes into ionization, exciting some of the electrons to higher energy levels. When the electrons jump back down to lower levels, they emit light, resulting in the auroras.

- Effectively, what has happened is a partial conversion of the solar wind's energy of motion into light. The different colors are due to various electronic transitions. For example, the typical red and green colors are due to transitions in neutral oxygen atoms.
- If you include the effects of the solar wind, the magnetic field of Earth looks different from that of a simple bar magnet. The solar wind particles interact with and complicate Earth's magnetic field significantly.
- The supply of particles from the Sun increases if there is a giant solar prominence. Also, there is a temporary restructuring of Earth's complex magnetosphere, and this releases a flood of particles that were trapped in it. Both effects tend to produce more collisions of charged particles with Earth's atmosphere, leading to a brighter auroral display.
- The changing distribution of particles and electrical currents can also lead to rapidly changing auroral displays.



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Aurorae are produced by interactions of solar flares and Earth's magnetic field producing a spectacular light show.

- For viewing auroras, the general rule is that the high latitudes on Earth are better than low latitudes close to the equator. In general, Canada gets more auroras than Europe or Asia per unit area of land.
- As we said, solar flares and coronal mass ejections supply new particles to Earth's magnetic field, but they also change the magnetic field configuration, causing electric currents and providing a supply of charged particles in Earth's atmosphere, sometimes even at latitudes closer to the equator.
- The southern lights are formed in the same way as the northern lights, but far fewer people see them because the main region of southern visibility is over the ocean and Antarctica.

Important Terms

aurora: The northern lights (*aurora borealis*) or southern lights (*aurora australis*); caused by energetic charged particles from the Sun interacting with atoms and molecules in Earth's upper atmosphere, making them glow.

chromosphere: The hot, thin layer of gas just below the Sun's corona and above the photosphere.

coronal mass ejection: A giant outburst of particles and radiation ejected by the Sun's surface and inner corona, generally from a larger region than a solar flare.

H-alpha: The photon absorbed when an electron in a hydrogen atom jumps from the second to the third energy level or the photon emitted when it jumps from the third to the second energy level.

photosphere: The visible surface of the Sun (or another star) from which light escapes into space.

plasma: Ionized gas; sometimes called a fourth state of matter.

shade 14 welder's glass: A filter that can be safely used to view the uneclipsed or partially eclipsed Sun; it cuts out about 99.999% of the light, including infrared and ultraviolet.

solar flare: An explosive release of energy from a relatively small portion of the Sun's surface; marked by extremely high temperatures and very high-speed particles.

sunspots: Cooler regions on the Sun's photosphere that appear as dark blotches on the photosphere. They have strong, tangled magnetic fields that block hotter plasma rising from the Sun's interior.

Van Allen belts: Regions in Earth's magnetosphere where there is a concentration of charged particles from the Sun and outer space.

Suggested Reading

Dickinson, *Nightwatch*.

Golub and Pasachoff, *Nearest Star*.

Levy, *David Levy's Guide to the Night Sky*.

Naylor, *Out of the Blue*.

Pasachoff and Filippenko. *The Cosmos*.

Questions to Consider

1. What is the delay (in minutes) between the detection on Earth of the visible light from a coronal mass ejection and the arrival of the fastest charged particles, assuming their speed is $1/5$ that of light? (Note: Earth's distance from the Sun is 8.3 light minutes.)
2. Large groups of sunspots can be relatively long-lived (a few weeks or a month), and they remain essentially fixed at the same physical location on the photosphere throughout their lives. Suppose a sunspot group appears to move from the center to the edge of the Sun's disk in 7 days. What is the approximate rotation period of the Sun?

3. Try monitoring the number of sunspots you see through shade 14 glass or (better yet) a Sunspotter as a function of time over the course of a few years. An observation every few weeks should suffice to establish a trend.
4. Keep track of the solar activity cycle by consulting the Internet, and make a point of going outside at night to search for auroras after major solar storms are reported.

Solar Eclipses—Marvelous Coincidences

Lecture 11

In the last lecture, we discussed the visible Sun and the effects of the solar wind on Earth in the form of auroras and power surges. Many satellite photos show the Sun's hot corona, which flows outward to form the solar wind. Normally, we cannot see the corona from Earth's surface, but sometimes, when the Moon is new and in the same general direction as the Sun, it can pass exactly along the Sun's line of sight, creating a total eclipse and revealing the ghostly, ethereal corona. This event provides a truly breathtaking view of the Sun.

The Positions of the Sun and the Moon

- Recall from Lecture 1 the striking coincidence that the Sun is 390 times larger than the Moon and 390 times farther away; this means that they both take up, or subtend, the same size in the sky, half a degree, and allows solar eclipses to occur.
- The Moon is slowly drifting away from Earth, and total eclipses are becoming more rare and shorter. In about half a billion years, they will not be possible at all.
- You might wonder why a solar eclipse does not happen every month at the time of a new Moon. Remember that the Moon's orbital plane is tilted by 5 degrees relative to Earth's orbital plane. This means that the new Moon is generally a bit above or below the Sun. The alignment is not perfect, but sometimes the Sun, the Moon, and Earth are collinear.
- Each year, there are at most 7 solar and lunar eclipses altogether. Most of these are partial. Total solar eclipses occur every 1.5 years on average, about the same as total lunar eclipses.

The Stages of a Solar Eclipse

- As the Moon orbits Earth and goes from west to east relative to the background sky, it first starts to cover the part of the Sun that faces west. This moment is known as first contact.
- After a bit more time, it looks as if a sizable chunk has been bitten out of the Sun, although it is not obvious that you are seeing a silhouette of the Moon.
- Over the course of about an hour, more of the Sun gets blocked, but the sky brightness does not change much until more than half the Sun is covered.
- About three-quarters of the way through the partial phases, the sky starts to darken noticeably, and near totality, the changes are strikingly rapid. Just before totality, the stunning **diamond ring** effect is seen. The moment when the eclipse is total is called second contact.
- At totality, you can see the chromosphere, the thin, hot layer outside the photosphere, and a few prominences. Outside the chromosphere is the even hotter corona, millions of degrees but very tenuous. It appears as delicate streamers.
- Earthshine is present on the Moon during a total solar eclipse, but it is difficult to see without blocking much of the light from the corona. You can also sometimes see the Moon's shadow on the atmosphere. The shadow can be most prominent when the Sun is close to the horizon and the view is without obstacles.



The moment of total solar eclipse is the best time to catch sight of the Sun's chromosphere and inner corona.

- The colors of the twilight sky appear near the horizon all around you. This is light filtering through from places outside the total eclipse, and the bluest and most violet rays get scattered out, just as with the normal twilight sky. Away from the horizon, the sky is darker, and you can see some of the brightest stars and planets.
- Near the end of totality, the chromosphere on the side that is about to be uncovered appears. Then, right after what is called third contact, another diamond ring appears. The whole sky is flooded with light as more and more of the Sun's photosphere becomes uncovered.

Baily's Beads

- The second diamond ring may look more spatially extended than the first. Several points of light are visible instead of just one, and these are called **Baily's beads**.
- The Moon has a slightly rough, serrated edge, and sunlight can shine through the low points along the edge just before second contact and just after third contact, producing Baily's beads.
- If the Moon's edge is particularly rough, Baily's beads can be especially numerous and long-lived.
- Having some clouds in the sky near totality actually adds to the drama and may allow you to see some iridescence.

Shadow Bands

- When the Sun is just a very thin sliver and is not blocked by clouds, you may see an effect called **shadow bands**. For a few minutes before or after totality, these appear as subtle dark and light ripples shimmering across a blank surface, such as the ground.
- Shadow bands are analogous to the ripples of light you can see at the bottom of a pool or on the sand in the shallow parts of the ocean. They are caused by turbulence in the atmosphere that is making the

Sun appear to twinkle. The Sun is so bright that you can actually see the places where it would appear brighter or darker than usual.

The Shadow of the Moon

- At any given moment, the Moon's shadow falls on just a small part of Earth, only about 150 miles wide at most. People within that dark shadow can see the fully eclipsed Sun.
- As the Moon orbits Earth, its shadow traces out a long path on Earth's surface from west to east. West to east is also the direction in which Earth rotates, partly compensating for the shadow's faster motion. The net result is that the shadow races along Earth's surface at speeds of up to a few thousand miles per hour.
- Totality usually lasts only 2–3 minutes, and the theoretical maximum is about 7.5 minutes. Totality lasts longest if you are viewing it from near the center of the shadow, on what is called the center line.
- Away from the center line, totality is shorter because the alignment is not as precise, but you actually do not lose much time unless you are relatively close to an edge of the path.
- Because the shadow falls on Earth's spherical surface, it appears curved, especially when mapped on a flat sheet of paper with the Mercator projection. The Moon's shadow falls over a wider area at the poles because it is nearly tangent to Earth's surface near the poles.
- As progressively more of the Sun becomes eclipsed, shadows of objects get sharper, especially in the direction perpendicular to the thin part of the crescent. That is because the Sun's rays are coming from a smaller range of directions from the thin crescent. If you look away from the Sun just before or after totality, you can even see shadows from individual hairs.

- In addition to using shade 14 welder's glass, another way to view an eclipse is to make a pinhole camera by punching one or more holes in a piece of cardboard and projecting the Sun's image onto a shaded viewing screen.

Annular Eclipses

- An **annular eclipse** is a special type of **partial eclipse**, so-named because the Sun looks like an annulus or ring.
- As mentioned in Lecture 8, the Moon's orbit is an ellipse. The Earth is displaced from the center of the ellipse by about 6%. This means that at its closest approach to Earth, the Moon is roughly 12% closer than it is at its farthest, and it looks 12% larger.
- When the Moon is farther than average from Earth, it does not appear as large as when it is close by, and thus, it is not big enough to fully block the Sun's photosphere. We get an annular eclipse instead of a total eclipse.
- Annular eclipses are actually slightly more frequent than total ones, but they also show some of the effects of totality. Near the beginning or end of an annular eclipse, you can often see some prominences or even a bit of corona on the side of the Sun that is barely covered.

Hybrid Eclipses

- **Hybrid eclipses** are a special combination of annular and total. From locations near the middle of the eclipse path, where Earth's surface bulges out and is closest to the Moon, the Moon appears large enough to give a total eclipse. From locations near the beginning and end of the eclipse path, the Moon is farther away, so it can appear too small to fully cover the Sun.

- Although totality is usually brief in hybrid eclipses, they provide a great chance to see Baily's beads, the chromosphere, and prominences all around the Sun, since the photosphere is just barely covered by the Moon.

Experiencing Eclipses

- Not much of Earth's surface experiences totality. In fact, on average, a total solar eclipse occurs roughly once per 4 centuries at a given location. An eclipse will not usually come to you; you have to go and seek it.
- Besides being in the path of totality, another major point of consideration is the weather. If your travel plans are flexible, try to choose an area with good to excellent chances of clear skies. Information about the eclipse and weather forecasts will be in the news and on the Internet, especially as the eclipse date approaches.
- Eclipses are produced by a marvelous coincidence that appears to have no cosmic purpose other than to please us. They are definitely among the things in life that should not be missed, if possible. Witnessing one can be a truly thrilling, awe-inspiring experience.

Important Terms

annular eclipse: A nearly total solar eclipse, but the Moon's angular size is not sufficiently large to fully block the Sun's photosphere. Occurs when the Moon is farther than average from Earth or when the Sun is closer than average to Earth due to the eccentricities of the orbits.

Baily's beads: Just before or after totality during a solar eclipse, the effect of sparkling lights created by sunlight passing through valleys on the Moon's surface.

diamond ring: The last few seconds before (and the first few seconds after) a total solar eclipse, when a tiny part of the Sun's photosphere is still visible, but the inner corona can also be seen, producing an apparent ring with a bright jewel.

partial eclipse: When only part of the Moon is in Earth's umbral shadow or when only part of the Sun is blocked by the Moon.

shadow bands: Subtle dark and light ripples shimmering along the ground for a few minutes before or after totality during a solar eclipse. Caused by the twinkling of the thin crescent Sun.

Suggested Reading

Dickinson, *Nightwatch*.

Espenak, *Fifty Year Canon of Solar Eclipses*.

Golub and Pasachoff, *Nearest Star*.

Harris and Talcott, *Chasing the Shadow*.

Littman, Willcox, and Espenak, *Totality*.

Naylor, *Out of the Blue*.

Pasachoff and Filippenko. *The Cosmos*.

Questions to Consider

1. Suppose the Moon were 3 times its current distance from Earth. What would the physical size of the Sun have to be, relative to its current physical size, for total solar eclipses to still be possible?
2. If a typical path of totality during a solar eclipse is roughly 8000 miles long and 100 miles wide, what is the fraction of the Earth's surface area covered by a single total solar eclipse? (Note: The Earth's radius R is about 3960 miles, and the surface area of a sphere is given by $4\pi R^2$.) Total solar eclipses occur roughly once every 1.5 years. So, what is the

approximate *average* time interval between total solar eclipses, as seen from a given point on Earth?

3. What is the minimum time interval between a lunar eclipse and a solar eclipse?
4. During a partial eclipse of the Sun, use creatively designed pinhole cameras to project many images of the Sun onto a shaded surface, forming a word or a pattern. Can you find images of the eclipsed Sun formed by natural pinhole cameras, such as the holes between leaves in trees?
5. Witness a total solar eclipse with a group of friends, preserving their reactions during the event with a tape recorder or video/audio camera.

Celestial Sights When the Night Is Darkest

Lecture 12

In this course, we have seen and discussed some amazing things to look for in the sky. In this final lecture, we will explore skywatching under optimal, very dark conditions. With the growth of cities and other sources of light pollution, really dark skies are becoming scarce. But if you find yourself out camping on a moonless night, far from city lights, you can see faint stars, the zodiacal light, the “counterglow,” and even other galaxies.

Great Sights in the Dark Sky

- The single greatest sight in the dark sky is the **Milky Way**. To see it well, your eyes must be dark-adapted, you need to be far from city lights, and you want no moonlight or auroral activity.
- At any given time in a dark, rural area, you can see, at most, 3000 stars in the visible celestial hemisphere. In brighter suburban areas, the number of visible stars drops to, at most, 1000.
- If you are viewing a truly dark sky, you might be able to see stars down to magnitude 7 or even a bit fainter. Other faint objects, such as the brightest asteroids or satellites in mid-Earth orbit, might be visible, as well.

The Zodiacal Light

- The **zodiacal light** appears as a faint glow above the western horizon after the end of evening twilight or above the eastern horizon before morning twilight. It is sometimes called the false dawn.

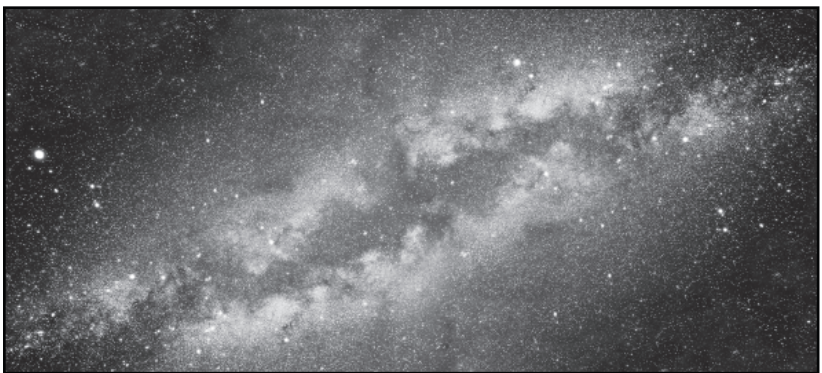
- Zodiacal light is actually sunlight reflected by interplanetary dust from the tails of comets, disintegrating comets, and asteroid collisions. It is a band of light along the zodiac, brightest near the Sun and fading as you look farther away.
- From the middle to far northern or middle to far southern latitudes, the zodiacal light is best seen after dusk in February, March, and April. That's because in the spring, the ecliptic makes a steep angle relative to the horizon at sunset. The zodiacal light is then visible high above the horizon.
- Around September or October, look for the light before dawn, because the autumn ecliptic makes a steep angle relative to the horizon at sunrise, not sunset. Close to the equator, the time of year does not matter as much, because the ecliptic makes a pretty steep angle relative to the horizon most of the year.

***Gegenschein*: The Counterglow**

- The phenomenon called *gegenschein* (“counterglow”) is related to zodiacal light, but it is much harder to see. It is a very faint patch of light in the dark sky directly opposite the Sun, highest near midnight.
- This counterglow is sunlight back-scattered by dust between the planets. In general, forward scattering of light by particles is the most efficient, but back-scattering can be thought of as the next most efficient. In this case, there is an excess of light from the direction opposite the Sun, the antisolar point.
- The counterglow also represents the back-scattering particles at full phase, similar to the full Moon, thus enhancing the effect and making them appear brighter.
- October is an especially favorable time for viewing the *gegenschein* because the antisolar point falls in the constellation Pisces, which is in a dark part of the sky.

The Milky Way

- The Milky Way is a **spiral galaxy**. If we could see it from above and outside, it would look like a disk with spiral arms. In the central region of a spiral galaxy, there is a bulge of old stars and a tiny nucleus that usually has a giant **black hole**.
- The entire disk of the Milky Way is about 100,000 light years across but just a few thousand light years in thickness. Our Sun is about 26,000 light years from the center of the disk.
- When we look away from the disk, we see relatively few stars in the dark night sky, but if we look through the disk, along the plane of our Galaxy, there are many stars. We see the collective light of hundreds of thousands of stars along the plane and progressively fewer stars as we look farther out of the plane at an angle. The stars form a band all around us, called a great circle.
- Notice that the Milky Way does not coincide with the ecliptic. The plane of our Galaxy and Earth's orbital plane, which defines the ecliptic, are offset by about 60 degrees. They intersect in Sagittarius and Gemini, so the planets are sometimes found in the Milky Way in those constellations.



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The Milky Way is a few thousand light years thick, and a thin layer of dust blocks light from distant stars.

- The Milky Way looks fairly splotchy. There are some brightly lit-up clouds of gas and star clusters, but there are also dark dust lanes. These are produced by interstellar clouds of gas and dust; the dust in particular tends to extinguish and redden the light of background stars.
- In some deep photos of the middle of our galaxy, you can see some of the bulge that makes one part of the Milky Way look thicker. This bulge is in Sagittarius.
- The brightest parts of the Milky Way are visible for much of the night during the summer in the Northern Hemisphere or winter in the Southern Hemisphere. Because of Earth's rotation, the predawn hours of spring and the early evening of fall are also good in the north.
- Observers in Earth's Southern Hemisphere have an advantage over Northern Hemisphere observers when it comes to viewing the Milky Way because the Galactic center gets much higher above the horizon there, and it is not as obscured by particles in our atmosphere or light pollution.
- If you spend some time scanning the skies, especially in and near the Milky Way, you can find all sorts of interesting spots of light. Use your planisphere, a phone or computer app, or the Internet to identify these objects.

Messier Objects

- Charles Messier, a French astronomer in the mid-18th century, catalogued stationary objects that he saw in the sky that might be mistaken for comets. A few of the Messier objects, such as the Pleiades star cluster, are quite bright.
- Most of the Messier objects are much fainter than the Pleiades. Although several dozen of them can be seen with the naked eye on a very dark night, you will get better views through even a small pair of 10×25 binoculars.

- Telescopes can provide even better views of many of these objects, especially if you use what is called averted vision and look toward the edge of the field of view in the eyepiece. This exposes the more sensitive part of your retina to the object.

Nebulae and Stars Viewed with Binoculars

- The sword of Orion contains a famous nebula, M42. This cloud of gas and dust, about 1500 light years away, is a stellar nursery. Four bright stars in the central part of the Orion nebula are known as the Trapezium.
- The M42 is an emission nebula, so-called because the atoms glow as a result of having been energized by ultraviolet light from the hot, massive, newly formed stars. Also present in the sky are reflection nebulae, which are blue for much the same reason that our daytime sky is blue: Interstellar dust scatters blue light from nearby stars better than red, so the nebulae look blue.
- In a few places, you can see some very dark nebulae. These dense clouds of gas and dust block starlight. In many of them, stars are still forming.
- If you travel to the equator or south of it, a beautiful view is the Centaurus-Cruz-Carina region of the Milky Way, which is visible in the evenings around February through July. Here, you can see Alpha and Beta Centauri, the Southern Cross, the Keyhole nebula, and one of the most massive stars known, Eta Carinae.
- In Scorpius, there are at least two naked-eye star clusters, M6 and M7. Clusters like these are called open star clusters because they have a somewhat irregular shape and are loosely bound by gravity.
- In Hercules, which is high in the evening sky in the Northern Hemisphere summer, you can see M13, a globular cluster. Globular clusters are basically the first objects formed in our Galaxy.

Galaxies Viewed with Binoculars

- The brightest galaxy you can see with binoculars is M31, the Andromeda galaxy. This galaxy, 2.5 million light years away, has dwarf satellite galaxies that orbit around it very slowly.
- Andromeda and its satellites are part of our Local Group, a gravitationally bound cluster of about 60 galaxies. Another member of the Local Group is the Triangulum galaxy, M33, which is about 3 million light years away.
- In the Southern Hemisphere, you can see the Large and Small Magellanic Clouds. They look like separate patches of the Milky Way, but they are actually dwarf galaxies in our Local Group.

Darkness

- The darkness of the night sky has profound implications concerning the origins of the Universe.
- Given a static, infinitely old, and infinitely large Universe uniformly filled with typical stars like the Sun, it's logical to think that the sky should be at least as bright as the surface of the Sun at all times.
- The fact that this is obviously not the case is known as **Olbers' paradox**, named after Wilhelm Olbers. At least one of the initial assumptions about the nature of the Universe must be wrong.
- The main resolution of Olbers' paradox is that the Universe is not infinitely old. In fact, it is only about 14 billion years old. Light from stars and galaxies that are farther away than about 14 billion light years has not had time to reach us yet, and there are simply not enough of these stars and galaxies at smaller distances to have made the sky bright.
- If the Universe has a finite age, it must have had a distinct beginning, and in fact, it did: the **Big Bang**. We think the Universe began in

a hot, dense initial state, and it has been cooling and expanding ever since.

- If we look far enough back into the past, shouldn't we see the Universe as it was when it was hot and ionized and, therefore, very bright? No, because the early optical light has stretched along with the expansion of space as the Universe cooled, and it is now in the radio part of the spectrum. This **cosmic microwave background radiation** is essentially the afterglow of the Big Bang.

Our Connection to the Cosmos

- The Tarantula nebula in the **Large Magellanic Cloud** is the largest stellar nursery in our Local Group of galaxies. On February 23, 1987, light from a massive dying star in this nebula, Supernova 1987A, reached Earth after traveling for about 170,000 years. It was the brightest exploding star in about 4 centuries.
- Exploding supernovas are incredibly important to us. Indeed, we owe our existence to them. Before and during the explosion, heavy elements are cooked up through nuclear reactions deep inside the star, then blasted into space.
- Over tens of thousands of years, these gases expand and thin out. Then, they coalesce and form gravitationally bound nebulae. When such a nebula collapses, new stars are formed, some of which have disks of gas and dust around them. Rocky, earthlike planets can form in such dusty disks, as our planet did 4.6 billion years ago.
- In Earth's case, self-replicating, primitive organisms spread throughout the planet's surface, and after billions of years of evolution, humans eventually developed.
- The late Carl Sagan said, "We are made of star stuff," meaning that most of the elements that make up our bodies were forged in the stars. Through skywatching and detailed studies of stars in the Universe, we can learn about the very origins of human life.

Important Terms

Big Bang: The birth of the Universe in a very hot, dense state 13.7 billion years ago, followed by the expansion of space.

black hole: A region of space in which the gravitational field is so strong that nothing, not even light, can escape. Predicted by Einstein's general theory of relativity.

cosmic microwave background radiation: Radio electromagnetic radiation that was produced in the hot Big Bang. It now corresponds to $T \approx 3$ K because of the expansion and cooling of the Universe.

gegenschein: A very faint patch of light in the dark night sky in the direction opposite the Sun; produced when sunlight is back-scattered by interplanetary dust.

Large Magellanic Cloud: A dwarf companion galaxy of our Milky Way Galaxy, about 170,000 light years away; best seen from Earth's Southern Hemisphere.

Milky Way: The faint band of light across the sky coming from the stars and gas in the plane of the Milky Way Galaxy (our Galaxy).

Olbers' paradox: The dark night sky; simple arguments suggest that it should be very bright.

spiral galaxy: One of the two major classes of galaxies defined by Edwin Hubble; made up of a roughly spherical central "bulge" containing older stars, surrounded by a thin disk in which spiral arms are present.

zodiacal light: A faint glow in the night sky around the ecliptic, stretching up from the western horizon shortly after evening twilight and up from the eastern horizon shortly before morning twilight; it is produced by sunlight reflected from interplanetary dust. If the light is seen far from the direction of the Sun, it is sometimes called the zodiacal band.

Suggested Reading

Dickinson, *Nightwatch*.

Edmund Scientific, *Edmund Mag 5 Star Atlas*.

Ferris, *Coming of Age in the Milky Way*.

Harrison, *Darkness at Night*.

Kitchen and Forrest, *Seeing Stars*.

Levy, *David Levy's Guide to the Night Sky*.

Marschall, *The Supernova Story*.

Naylor, *Out of the Blue*.

Pasachoff and Filippenko. *The Cosmos*.

Rey, *Find the Constellations*.

Rey, *The Stars*.

Ridpath, *Norton's Star Atlas*.

Tirion, *The Cambridge Star Atlas*.

Questions to Consider

1. To a reasonably good first approximation, the number of naked-eye stars per unit area of the sky is independent of the direction you look along the Milky Way. To 19th-century astronomers, this suggested that the Sun is near the center of our Milky Way Galaxy. Instead, however, it is roughly two-thirds of the way from the center to the edge. What might account for the impression that we are near the center?
2. Choose a region of the sky and count how many naked-eye stars you can see in it. Do this on many nights from the same location, spanning the full range of lunar phases. Does the number of visible stars depend on how much the sky is illuminated by moonlight? Also, try counting the number of stars while in a big, bright city, and at different distances from this city.

3. Are you convinced that Olbers' paradox really does present a problem whose main possible solutions are profound? Can you think of any other solutions, besides those discussed in the lecture?
4. How might supernovae be used to determine the distances of very distant galaxies?

The Best Annual Meteor Showers

The Best Annual Meteor Showers

Shower Name	Date of Maximum	Range of Dates	Maximum Rate per Hour	Radiant Constellation	Parent Body
Quadrantids	Jan. 3/4	Dec. 29–Jan. 7	60–100	Bootes	Asteroid 2003 EH1
Lyrids	April 21/22	April 16–26	10	Lyra	Comet Thatcher
Eta Aquarids	May 5/6	April 21–May 12	10–30	Aquarius	Comet Halley
Delta Aquarids	July 29/30 Aug. 13/14	July 14–Aug. 18 July 16–Sept. 10	15–20 10	Aquarius Pisces	Unknown (double shower)
Perseids	Aug. 12	July 23–Aug. 20	70–80	Perseus	Comet Swift-Tuttle
Orionids	Oct. 20–22	Oct. 16–27	20–30	Orion	Comet Halley
Taurids	Nov. 8	Nov. 5–12	5–8	Taurus	Comet Encke
Leonids	Nov. 17	Nov. 14–20	10	Leo	Comet Tempel-Tuttle
Geminids	Dec. 13/14	Dec. 7–17	60–80	Gemini	Asteroid Phaethon
Ursids	Dec. 22/23	Dec. 17–25	10	Ursa Minor	Comet Tuttle

Clouds

Clouds are regions of the atmosphere where water vapor has condensed to form water droplets or ice crystals.

Clouds in the troposphere have three broad types, first identified and named by Luke Howard in 1802 (published in 1803 as *On the Modifications of Clouds*):

- cirrus: thin, wispy, high-altitude clouds consisting of ice crystals
- stratus: horizontally extended layers or sheets but not very thick; they consist of water droplets and/or ice crystals
- cumulus: heaped or puffy clouds having considerable vertical extent; they consist of water droplets

Genera of Clouds

Luke Howard's original system also included 4 derivative forms: Cirro-stratus, Cirro-cumulus, Cumulo-stratus, and Cumulo-cirro-stratus, which he also called Nimbus (today called *Nimbostratus*). His system was refined during the 19th century, and by 1896, an *International Cloud Atlas* was issued that subdivided the 3 major categories into a total of 10 genera.

The main additional variable is the height of the cloud base: high-level clouds above about 4 miles (20,000 ft; 6 km) are *Cirrus*, *Cirrostratus*, and *Cirrocumulus*. Mid-level clouds from roughly 1 to 4 miles (6,500–20,000 ft; 2–6 km) are *Altostratus* and *Altostratus*. Low-level clouds below about 1 mile (starting below 6500 ft; 2 km) are *Stratus*, *Nimbostratus*, *Stratocumulus*, and some *Cumulus*. Clouds starting from a low base but capable of spanning a wide range of heights are *Cumulonimbus* and some *Cumulus*.

	Cirrus	Stratus	Cumulus
high-level clouds (above ~4 miles)	<i>Cirrus</i> (Ci)	<i>Cirrostratus</i> (Cs)	<i>Cirrocumulus</i> (Cc)
mid-level clouds (1 to 4 miles)		<i>Altostratus</i> (As)	<i>Alto cumulus</i> (Ac)
low-level clouds (below ~1 mile)		<i>Nimbostratus</i> (Ns) <i>Stratus</i> (St)	<i>Stratocumulus</i> (Sc)
spanning a wide range of heights			<i>Cumulonimbus</i> (Cb; not Cn) <i>Cumulus</i> (Cu)

The 4 stratus genera are layer clouds that differ by thickness. *Cirrostratus* are especially thin and allow solar and lunar halos. *Altostratus* can let sunlight partially through but without halo phenomena. *Stratus* is the familiar gray drizzle or snow cloud, with halos possible only at very low temperatures. *Nimbostratus* is a darker rain or snow cloud that blocks out the Sun entirely. (“Nimbo” or “nimbus” was the term Luke Howard had introduced to refer to clouds capable of substantial precipitation.)

The 5 *Cumulus* genera have different kinds of puffy heaps: regular and smallest for *Cirrocumulus* (less than 1 degree across the sky for each heap), regular and intermediate for *Alto cumulus* (1–5 degrees each), regular and large for *Stratocumulus* (greater than 5 degrees each). *Cumulus* are detached clouds with the sort of clearly defined mounds and domes that children commonly draw. *Cumulonimbus* are heavy and dark, with a smooth or flattened “anvil” or plume on top, and can produce rain, snow, or hail.

In the 20th century, most of the 10 genera were further subdivided into species and varieties, as summarized in the 1956 edition of the *International Cloud Atlas*, published by the World Meteorological Organization (WMO). The

exceptions are *Altostratus* (which has no species), *Cumulonimbus* (which has no varieties), and *Nimbostratus* (which has neither species nor varieties).

Species of Clouds

There are 16 different species words, some of which are unique to a single genus. *Cumulus*, for example, has 3 species all its own for comparing height versus width, as follows:

- *Cumulus humilis*: width greater than height
- *Cumulus mediocris*: width roughly equal to height
- *Cumulus congestus*: height greater than width

Wispier clouds are either *Cumulus fractus* or *Stratus fractus*. Moreover, the same species words can be reused across more than one genus. For example, *Cirrocumulus*, *Alto cumulus*, and *Stratocumulus* each have both *lenticularis* (“lens”) shape and *stratiformis* (“flattened”) shape.

Cirrus has 5 species, which differ depending on the shape and thickness of the wispy strands:

- *fibratus* (“fibrous”): straight or irregular fibers, usually distinct, with no special tufts or hooks
- *uncinus* (“hooked”): hooked at the end like a comma
- *floccus* (“tufts”): small, rounded tufts at the end
- *castellanus* (“castle”): thicker tufts resembling turrets rising from a shared base
- *spissatus* (“thickening”): denser patches instead of distinct fibers; often formed from the top of a *Cumulonimbus*

There are only a few other species. *Cirrostratus* can be *fibratus* (“fibrous”) or *nebulosus* (“full of mist”); *Stratus* and *Cumulus* can be *fractus* (“fractured”) or *nebulosus*. And *Cumulonimbus* has 2 species all to itself: *calvus* (“bald”) and *capillatus* (“hairy”).

Varieties of Clouds

Beyond the species, there are 9 possible varieties, which are easier to understand than the species. Of the varieties, 4 are based on how much light gets through:

- *translucidus*: able to see the Sun or the Moon
- *lacunosus*: lots of regular holes
- *perlucidus*: can see bits of blue sky
- *opacus*: neither the Sun nor the Moon is visible

The other 5 varieties are based on shapes:

- *duplicatus*: has 2 similar layers; typical of *Cirrus fibratus* and *Cirrus uncinus*
- *radiatus*: has rays
- *undulatus*: has waves
- *vertebratus* (“ribs”): has a regular shape like a fish skeleton; usually *Cirrus*
- *intortus* (“twisted”): irregular shape

In addition to the genera, species, and varieties, clouds can be described in terms of supplementary features, the most common of which across all cloud genera are the *virga*, which we discussed in Lecture 2, and *praecipitatio* (“falling”), which describes clouds with visible as the name suggests are when fallstreaks are visible from the cloud to the ground.

Other supplementary features refer to unusual shapes, including mamma (“udder”), pannus (“tattered”), pileus (“cap”), velum (“sail of a ship”), tuba (“trumpet”), incus (“anvil”), and arcus (“arch”).

Clouds beyond the Troposphere

Since the beginning of the 20th century, it has been known that clouds can also be seen beyond the troposphere.

In the stratosphere, 10–20 miles high (15–30 km), are the nacreous clouds (“mother-of-pearl” clouds), discussed in Lecture 5, which resemble either *Cirrus* or *Alto cumulus lenticularis* but are subdivided based on chemistry rather than shape. Viewing their intense colors is best in relatively northern latitudes during the first two hours after sunset or before sunrise, though they can also be seen less dramatically in moonlight or even during the day.

Clouds higher than 50 miles (80 km) above Earth’s surface are in the mesosphere and are the noctilucent clouds, mentioned in Lecture 5. Resembling *Cirrus* but with more vivid colors, they are most likely to be seen around midnight in a dark sky at latitudes of 50–65 degrees during a Northern Hemisphere summer.

Timeline

- 4th c. B.C..... Curved shape of Earth visible on the Moon during lunar eclipses used by Aristotle as evidence that Earth is a sphere.
- ~135 B.C. Catalog of the positions and apparent brightnesses of at least 850 stars compiled by Hipparchus.
- ~150 Claudius Ptolemy publishes the *Almagest*, in which the mathematical details of his new geocentric model of planetary motion are described.
- ~200 Dark region between the primary and secondary rainbows considered by (and later named for) Alexander of Aphrodisias.
- 1543..... Retrograde motions of Mars, Jupiter, and Saturn explained by the heliocentric theory of Nicolaus Copernicus.
- 1572..... Tycho Brahe studies a bright supernova (now named in his honor) and concludes that it is a new star in the stellar sphere beyond the planets.

1609–1610.....	Galileo Galilei first uses a telescope for celestial observations, discovering four moons of Jupiter, the complete set of phases of Venus, features on the Moon, and countless stars in the band of light called the Milky Way.
1609–1619.....	Johannes Kepler’s three laws of planetary motion.
1647.....	The first accurate map of Moon features, calling the dark areas “seas” (maria), produced by German brewer and astronomer Johannes Helvelius and his wife, Elisabetha.
1651.....	A Moon map naming major craters after Tycho, Kepler, and Copernicus produced by Italian Jesuit astronomers Giovanni Riccioli and Francesco Grimaldi.
1670–1672.....	Isaac Newton conducts experiments with light and optics, demonstrating that white light consists of all the colors of the rainbow.
1684.....	Zodiacal light correctly explained as sunlight reflecting off interplanetary dust by Niccolo Fatio de Duilliers.

- 1705..... Edmond Halley suggests that the comets of 1456, 1531, 1607, and 1682 were all the same object and correctly predicts the return (in 1758) of what is now called Halley's Comet (with later appearances in 1835, 1910, and 1986 and expected in 2061).
- 1781..... Uranus identified as a planet by Sir William Herschel.
- 1784..... Charles Messier's catalog of more than 100 objects we now know as nebulae, star clusters, and galaxies.
- 1801..... First asteroid discovered (Ceres), followed by 3 more over the next 6 years.
- 1802..... Cloud types, including cumulus, cirrus, and stratus, identified and named by Luke Howard.
- 1804..... Supernumerary bows of a rainbow explained by Thomas Young using a wave theory of light.
- 1820..... Faint patch of light above the upper tangent arc of a solar halo first described by Arctic explorer Sir William Parry and later named in his honor (Parry's arc).
- 1836..... Beads of light seen at the beginning or end of a total solar eclipse vividly described by Francis Baily and later named in his honor (Baily's beads).

1838.....	Distance of a light year first calculated by Friedrich Bessel.
1843.....	Sunspot cycle of 11 years first noticed by Heinrich Schwabe.
1846.....	Neptune identified as a planet by Johann Galle, following predictions by Urbain Le Verrier and John Couch Adams.
1854.....	Discovery of a faint patch of zodiacal light opposite the Sun (<i>gegenschein</i> , “counterglow”) by Danish astronomer Theodor Brorsen.
1859.....	Solar flares identified and their influence on auroras suggested during what were probably the brightest solar flares and auroral events of the past 200 years.
1871.....	Corona of the Sun shown to be an independent layer beyond the photosphere and chromosphere, not just a result of reflection or diffraction.
1871.....	The blue color of the sky explained by Lord Rayleigh’s analysis of how sunlight scatters in Earth’s atmosphere.
1885.....	High-altitude clouds first observed after the eruption of Krakatoa, though not named “noctilucent” and explained as mesosphere ice crystals until the 1930s.
1893.....	Nacreous (“mother-of-pearl”) clouds in the stratosphere first identified by Henrik Mohn.

1896.....	First edition of the <i>International Cloud Atlas</i> .
1902.....	Stratosphere independently discovered by Richard Assmann and Léon Teisserenc de Bort (who named both the stratosphere and troposphere).
1910–1920.....	Positive and negative ions from the Sun first discussed.
1923.....	Distance to the Andromeda nebula estimated by Edwin Hubble, confirming it as a separate galaxy outside our Milky Way galaxy.
1945.....	Idea for what are now called geostationary satellites proposed by Arthur C. Clarke.
1950.....	“Mesosphere” proposed as the name for the layer of atmosphere above the stratosphere by Sydney Chapman.
1956.....	New edition of the <i>International Cloud Atlas</i> categorizes clouds into 10 genera, 14 species, and 9 general varieties.
1958.....	Solar wind explained and named by Eugene Parker.
1964.....	Cosmic microwave background radiation, the afterglow of the hot Big Bang at the beginning of the universe, discovered by Arno Penzias and Robert Wilson.

1989.....	First photographs of red flashes of light (“red sprites”) above thunderstorms.
1994.....	First photographs of “blue jets” of light shooting upward from the tops of thunder clouds.
2008.....	A bright flash of gamma rays on March 19 at a distance of about 7.5 billion light years briefly becomes the most distant object potentially visible with the naked eye.
2011.....	Total lunar eclipse visible on December 10, primarily in Australia and Asia but also in western North America.
2012.....	Venus and Jupiter close to each other in mid-March.
2012.....	Annular solar eclipse on May 20; in the United States, visible from northern California to west Texas.
2012.....	Venus transits in front of the Sun (June 5/6) for the last time this century.
2012.....	Total solar eclipse on November 13/14; visible in Australia, New Zealand, and the South Pacific.
2012.....	Venus and Saturn very close to each other in late November.
2013.....	Venus and Jupiter very close to each other in late May.

2013.....	Venus and Mercury close to each other in mid-June.
2013.....	Annular solar eclipse on May 10; visible in Australia, New Zealand, and the Central Pacific.
2013.....	Mars and Jupiter very close to each other in July.
2013.....	Hybrid solar eclipse on November 3; total visible over parts of the Atlantic Ocean and central Africa.
2014.....	Total lunar eclipse on April 15; visible in North and South America and eastern Australia.
2014.....	Mars and Saturn close to each other in late August.
2014.....	Total lunar eclipse on October 8; visible in North America, Asia, and Australia.
2015.....	Venus and Mars very close to each other in mid-February and early November and reasonably close to each other in late August.
2015.....	Total solar eclipse on March 20; visible in the North Atlantic, the Faeroe Islands, and Svalbard.
2015.....	Total lunar eclipse on April 4; visible in western North America, Asia, and Australia.

2015.....	Venus and Jupiter very close to each other in late June and early July.
2015.....	Total lunar eclipse on September 28; visible in North and South America, Africa, and Europe.
2016.....	Venus and Saturn very close to each other in early January.
2016.....	Total solar eclipse on March 9; visible in Sumatra, Borneo, Sulawesi, and the Pacific.
2016.....	Mercury transits in front of the Sun on May 9.
2016.....	Venus and Jupiter very close to each other in late August.
2017.....	A terrific opportunity to see a total solar eclipse, which on August 21 passes across North America from northwest to southeast, crossing Oregon, Idaho, Wyoming, Nebraska, Missouri, the southern tip of Illinois, western Kentucky, Tennessee, the western tip of North Carolina, and South Carolina.
2018.....	Total lunar eclipse on January 31; visible in Australia, Asia, and western North America.
2018.....	Total lunar eclipse on July 27; visible in Europe, Africa, Asia, and Australia.

2019.....	Total lunar eclipse on January 21; visible in North and South America, Europe, and West Africa.
2019.....	Venus and Jupiter close to each other in late January and late November.
2019.....	Total solar eclipse on July 2; visible in the South Pacific, Chile, and Argentina.
2019.....	Mercury transits in front of the Sun on November 11.
2020.....	Total solar eclipse on December 14; visible in the South Pacific, Chile, Argentina, and the South Atlantic.
2020.....	A conjunction of Jupiter and Saturn (late December).
2024.....	Another great opportunity to see a total solar eclipse in North America, which on April 8 crosses Mexico, Texas, Oklahoma, Arkansas, Missouri, Illinois, Indiana, Ohio, New York, Vermont, New Hampshire, Maine, and New Brunswick.

Glossary

absorption line: A wavelength (or small range of wavelengths) at which the brightness of a spectrum is less than it is at neighboring wavelengths.

aerosol: Small particles of liquid or solid, typically about 1 to 100 micrometers in diameter, suspended in Earth's atmosphere.

airlight: Sunlight that has been reflected (scattered) by air molecules in Earth's atmosphere. It tends to be blue because Rayleigh scattering is more efficient at short wavelengths than at long wavelengths.

Alexander's dark band: The relatively dark region of the sky between the primary and secondary rainbows. Named in honor of Alexander of Aphrodisias, who considered it about 1800 years ago.

alpenglow: Highly filtered sunlight (typically yellow, orange, or pink in color) seen shortly before sunset or after sunrise, reflecting off mountains. It can be especially beautiful when the mountains are covered with snow or glaciers.

altitude: The number of degrees between an object and the horizon directly below it; the zenith has an altitude of 90 degrees, for example. Alternatively, the height of an object (such as a cloud) above Earth's surface, typically measured in miles or kilometers.

Andromeda galaxy: The nearest large galaxy to our own Milky Way galaxy; about 2.5 million light years away.

angstrom (Å): A unit of length commonly used for visible wavelengths of light; $1 \text{ Å} = 10^{-8} \text{ cm}$.

angular size: The angle in the sky taken up (subtended) by an object, as seen by us. The angular distance from the horizon to the zenith is 90 degrees.

annular eclipse: A nearly total solar eclipse, but the Moon's angular size is not sufficiently large to fully block the Sun's photosphere. Occurs when the Moon is farther than average from Earth or when the Sun is closer than average to Earth due to the eccentricities of the orbits.

antisolar point: The direction in the sky that is directly opposite the Sun, as seen by a given observer from a given location. It coincides with the shadow of the observer's head.

antitwilight arch: The band of pinkish light in the east shortly after sunset or in the west shortly before sunrise. Produced by air that is still illuminated by direct but highly filtered sunlight. Also known as the Belt of Venus.

apogee: In an orbit, the point that is most distant from the Earth.

apparent brightness: The amount of energy received from an object per second, per square centimeter of collecting area. It is related to luminosity and distance through the equation $b = L/(4\pi d^2)$, the inverse-square law of light.

apparent magnitude: See **magnitude**.

asterism: An easily recognizable grouping of stars that is not itself a full constellation but is part of one or more constellations. The Big Dipper is one example; it is part of Ursa Major, the Great Bear.

asteroid: A small body (smaller than a planet), in most cases consisting of rock or iron, that generally orbits the Sun between Mars and Jupiter.

astrology: The non-scientific belief that the positions of the Sun and various planets at the time of birth significantly affect one's life and personality. There is no significant evidence that astrology is correct and no physical mechanism or explanation for the alleged effects.

astronomical unit (AU): The average distance between the Sun and the Earth (1.5×10^8 km).

astronomy: The science that concentrates on the physical study of the universe and its large-scale contents, including planets, stars, galaxies, and the space between them; now essentially synonymous with astrophysics.

atmosphere: The layer of air that surrounds Earth's surface, confined mostly to a height of 60 miles or less; usually divided into the troposphere, stratosphere, mesosphere, and (above 60 miles) ionosphere. Other planets have atmospheres, too. The Sun's atmosphere consists of its chromosphere and corona.

aureole: A circular patch of light around the Sun, usually colorless, formed by sunlight that has been forward-scattered by aerosols in Earth's atmosphere. Also, the central patch of colorless light in a lunar or solar corona formed by the interaction of sunlight with water droplets in clouds.

aurora: The northern lights (aurora borealis) or southern lights (aurora australis); caused by energetic charged particles from the Sun interacting with atoms and molecules in Earth's upper atmosphere, making them glow.

Baily's beads: Just before or after totality during a solar eclipse, the effect of sparkling lights created by sunlight passing through valleys on the Moon's surface.

ball lightning: A roughly spherical glowing orb that may be a rare form of atmospheric electrical phenomenon, though it is poorly documented and might not actually exist.

Belt of Venus: See **antitwilight arch**.

Big Bang: The birth of the universe in a very hot, dense state 13.7 billion years ago, followed by the expansion of space.

binary star: Two stars gravitationally bound to (and orbiting) each other.

binoculars: Two small refracting telescopes joined together, producing magnified and brighter images of distant objects.

black body: An object that absorbs all radiation that hits it; none is transmitted or reflected. It emits radiation due to thermal (random) motions of its constituent particles, with a spectrum that depends only on the temperature of the object.

black hole: A region of space in which the gravitational field is so strong that nothing, not even light, can escape. Predicted by Einstein's general theory of relativity.

blue jet: A rare form of upward-moving lightning that starts from the top of a thundercloud and has a bluish color.

blue moon: An informal expression used to refer to rare events, as in "once in a blue moon." Formally, the second full Moon in a single calendar month or (even more correctly) the third full Moon in a season that has four full Moons instead of the usual three. Also, a very rare atmospheric condition in which the Moon appears blue due to the presence of particles that selectively scatter away redder (longer) wavelengths of visible light.

bolide: An exceptionally bright meteor. A very bright fireball is often called a bolide, especially if it breaks up into many pieces while streaking through the atmosphere.

Brocken spectre: A long shadow of a person produced on a lower layer of clouds, fog, or mist shortly after sunrise or before sunset; named after Brocken peak in the foggy Harz Mountains of Germany, from which it is often visible. Sometimes, a colorful glory will surround the shadow of a person's head.

CCD: Charge-coupled device. A solid-state imaging chip whose properties include high sensitivity, large dynamic range, and linearity.

celestial equator: The projection of Earth's equator onto the celestial sphere, forming a great circle that divides the celestial sphere into a northern hemisphere and a southern hemisphere.

celestial pole: The projection of the Earth's North or South Pole onto the celestial sphere. The sky rotates around the celestial poles from east to west.

celestial sphere: The enormous sphere, centered on the Earth, to which the stars appear to be fixed.

chromosphere: The hot, thin layer of gas just below the Sun's corona and above the photosphere.

circumhorizontal arc: A band of light having the colors of the rainbow, parallel to the horizon and not much above it, at least 46 degrees away from the Sun. Formed by sunlight passing through roughly horizontal, plate-like ice crystals.

circumpolar star: As seen from a given location, a star that circles the celestial pole and never sets below the horizon.

circumscribed halo: A rare halo around the common 22-degree solar halo, formed when the Sun is sufficiently high above the horizon and the upper and lower tangent arcs grow longer and join together .

circumzenithal arc: An arc of light having the colors of the rainbow in reverse that partly circles the zenith and is at least 46 degrees away from the Sun. Formed by sunlight passing through roughly horizontal, plate-like ice crystals.

cloud iridescence: Colorful bands or spots in clouds, formed by diffraction of sunlight by water droplets spanning a range of sizes in clouds. Closely related to the solar corona that is formed when droplets of uniform size diffract sunlight but more chaotic in appearance.

clouds: Regions of the atmosphere where water vapor has condensed to form water droplets or ice crystals. The three main cloud types are cirrus (thin, wispy, high-altitude clouds consisting of ice crystals), stratus (horizontally extended layers or sheets but not very thick; they consist of water droplets and/or ice crystals), and cumulus (heaped or puffy clouds having considerable vertical extent; they consist of water droplets). These

three major categories are subdivided into a total of 10 genera whose main additional variable is the height of the cloud *base*: high-level clouds above about 4 miles (cirrus, cirrostratus, cirrocumulus), mid-level clouds from roughly 1 to 4 miles (altocumulus, altostratus), low-level clouds below about 1 mile (stratus, nimbostratus, stratocumulus, cumulus), and clouds spanning a wide range of heights (cumulonimbus). “Nimbo” or “nimbus” refers to clouds capable of substantial precipitation.

comet: An interplanetary chunk of ice and rock (sometimes called a “dirty snowball” or an “icy dirtball”), usually in a very eccentric (elongated) orbit. Comets can partly evaporate (sublimate) when relatively near the Sun, forming a diffuse patch of light in the sky (a “coma” and sometimes a long “tail”) that consists of glowing ionized gas, as well as reflected sunlight.

condensation trail: A thin white streak following the jet engine of an airplane, caused by the condensation of moisture from the engine exhaust. Also known simply as a contrail.

conjunction: A planet is said to be in conjunction when it appears in the same (or nearly the same) direction as the Sun in the sky. Two planets are in conjunction when they are near each other in the sky (formally, they have the same celestial longitude).

constellation: One of 88 regions into which the celestial sphere is divided. The pattern of visible stars within a constellation is often named in honor of a god, person, or animal.

convection: Process by which bubbles of gas or liquid repeatedly heat and expand, rise and give off energy, and fall again; seen in the Sun, stars, Earth’s atmosphere, and Earth’s core.

corona: The very hot, tenuous, outermost region of the Sun, seen during a total solar eclipse. Also, a colorful set of rings around the Sun or Moon, produced by the interaction of light with uniformly sized water droplets in tropospheric clouds. The smaller the droplets, the larger the radius of the corona.

coronal mass ejection: A giant outburst of particles and radiation ejected by the Sun's surface and inner corona, generally from a larger region than a solar flare.

cosmic microwave background radiation: Radio electromagnetic radiation that was produced in the hot Big Bang. It now corresponds to $T \approx 3$ K because of the expansion and cooling of the universe.

cosmic rays: High-energy protons and other charged particles, probably formed by supernovae and other violent processes.

cosmology: The study of the overall structure and evolution of the universe.

crater: A generally circular region on a moon or planet produced by the impact of an asteroid or meteoroid. There are also volcanic craters made by eruptions.

crepuscular rays: Beams of light shining through gaps in clouds, usually best seen near sunset or sunrise. Also informally known as Buddha's rays, fingers of God, or Sun rays. If seen in the direction opposite the Sun, they are sometimes called anticrepuscular rays.

dark adaptation: The process by which one's eyes gradually see fainter objects in the dark. Pupils dilate, and the rods (rather than the cones) in the retina are activated.

degree: A unit of angular measure, $1/360$ of a full circle. The angle between the horizon and the zenith is 90 degrees, for example.

density: Mass per unit volume or, in some cases, the number of particles per unit volume (usually referred to as "number density").

diamond ring: The last few seconds before (and the first few seconds after) a total solar eclipse, when a tiny part of the Sun's photosphere is still visible, but the inner corona can also be seen, producing an apparent ring with a bright jewel.

diffraction: A phenomenon affecting light as it passes any obstacle, spreading it out and producing an interference pattern. This occurs best when the size of the obstacle is roughly comparable to the wavelength of light.

dipole field: The pattern of electric field lines produced by a pair of equal and opposite electric charges or of magnetic field lines surrounding a bar magnet.

dispersion: The spreading out of the different colors, or wavelengths, of light into a spectrum when it passes from one substance to another and gets refracted. For almost all substances, short wavelengths are bent more than long wavelengths.

Doppler shift: The change in wavelength or frequency produced when a source of waves and the observer move relative to each other. Blueshifts (to shorter wavelengths) and redshifts (to longer wavelengths) are associated with approach and recession, respectively.

dust: Interstellar dust consists of very fine particulate matter, typically just a small fraction of a millimeter in size. It tends to scatter starlight, especially the shorter (bluer) wavelengths.

earthshine: Sunlight illuminating the Moon after having been reflected from the Earth.

Earth's shadow: A dark band just below the antitwilight arch, visible shortly after sunset or before sunrise; the Earth blocks direct sunlight from reaching air. A related "dark segment" is sometimes seen just before sunset or after sunrise, caused by the atmosphere blocking sunlight that is passing through.

eccentric: Deviating from a circle. *Eccentricity* is a measure of this; ellipses of greater eccentricity are less circular.

eclipse: The passage of one celestial body into the shadow of another or the obscuration of one celestial body by another body passing in front of it. From Earth, we see solar eclipses when the Moon passes in front of the Sun and lunar eclipses when the Moon goes into Earth's shadow.

ecliptic: The path followed by the Sun across the celestial sphere in the course of a year.

electromagnetic force: One of the four fundamental forces of nature; it holds electrons in atoms.

electromagnetic radiation: Self-propagating, oscillating electric and magnetic fields. From shortest to longest wavelengths: gamma rays, X-rays, ultraviolet, optical (visible), infrared, and radio.

electron: Low-mass, negatively charged fundamental particle that normally “orbits” an atomic nucleus.

ellipse: A set of points (curve) such that the sum of the distances to two given points (foci) is constant.

elliptical galaxy: One of the two major classes of galaxies defined by Edwin Hubble; has a roughly spherical or elliptical distribution of generally older stars, less gas and dust, and less rotation than its spiral counterpart.

elongation: The apparent angular separation of a celestial object from the Sun, as seen from Earth.

emission line: A wavelength (or small range of wavelengths) at which the brightness of a spectrum is more than it is at neighboring wavelengths.

equator: On a planet’s surface, the great circle midway between the two poles.

equinox: One of two points of intersection between the ecliptic and the celestial equator or the time of the year when the Sun is at this position.

exoplanet: A planet orbiting a star other than the Sun; also known as an *extrasolar planet*.

extinction: The obscuration of starlight by interstellar gas and dust or the dimming of the Sun caused by molecules and dust particles in Earth's atmosphere.

extrasolar planet: See **exoplanet**.

eyepiece: A small tube containing a lens (or combination of lenses) at the eye end of a telescope; used to examine the image.

fireball: An extremely bright meteor; also known as a bolide, if exceptionally bright.

fog: Tiny (typically 0.05–0.1 mm) drops of water that have condensed out of moist air. In some cases, fog is simply the inside of a cloud, such as a stratus cloud. Generally, however, fog refers to condensation that forms in air whose moisture was produced locally, such as from a lake or wet ground.

fogbow: A rainbow formed by fog. Usually faint and nearly colorless, it has a smaller angular size than a normal rainbow, though it's somewhat wider and more diffuse.

frequency: For a wave, the number of waves per second that pass by a given point.

galactic cannibalism: The swallowing of one galaxy by another.

galaxy: A large (typically 5000 to 200,000 light years in diameter), gravitationally bound system of tens of millions (and up to a trillion) stars. The Large and Small Magellanic Clouds are satellite galaxies orbiting our Milky Way galaxy, and the Andromeda galaxy (M31) is the nearest large galaxy.

Galilean satellites: The four large moons of Jupiter (Io, Europa, Ganymede, Callisto), discovered by Galileo Galilei in 1609 when he used a telescope for celestial observations.

gamma rays: Electromagnetic radiation with wavelengths shorter than about 0.1 Å.

gamma-ray burst (GRB): A brief burst of gamma rays in the sky, now known to generally come from exceedingly powerful, distant objects.

gegenschein: A very faint patch of light in the dark night sky in the direction opposite the Sun; produced when sunlight is back-scattered by interplanetary dust.

general theory of relativity: Einstein's comprehensive theory of mass (energy), space, and time; it states that mass and energy produce a curvature of space-time that we associate with the force of gravity.

geocentric hypothesis: A model in which the Sun, Moon, planets, and stars rotate around the central, stationary, nonrotating Earth.

geostationary satellite: Generally refers to an artificial satellite that orbits Earth above the equator at the same rate at which Earth rotates; the satellite remains above the same location on Earth at all times.

giant planets: See **Jovian planets**.

gibbous: The phase of the Moon when it appears between half lit ("quarter Moon") and fully lit ("full Moon"). Can apply to the appearance of a planet, as well.

glitter path: Sunlight or moonlight (or light from another source, such as a lamp) reflecting off the rough surface of water or snow, forming a column of light that can shimmer with time.

globular cluster: A bound, dense, spherically symmetric collection of stars formed at the same time.

glory: An often colorful halo of light around the shadow of an object projected on a cloud or fog; caused by the refraction, reflection, and interference of light passing through water droplets.

GPS satellite: An artificial satellite in mid-Earth orbit, used for the global positioning system (GPS).

graupel: Soft, hail-like pellets that form in a cloud having a strong updraft, where water droplets can supercool and then freeze when they hit ice crystals.

gravity: The weakest of nature's fundamental forces but the dominant force over large distances because it is cumulative; all matter and energy contribute, regardless of charge.

great circle: The intersection of a sphere with a plane passing through the center of the sphere. The meridian and the celestial equator are both great circles.

green flash: A subtle green glow sometimes visible in very clear skies just as the last part of the Sun is setting (or the first part is rising). Caused by atmospheric refraction and mirages.

halo: A circle of light centered on the Sun or Moon, usually having a radius of about 22 degrees; it is formed by light passing through randomly oriented, hexagonal, pencil-shaped ice crystals, generally in cirrus or cirrostratus clouds. A larger, fainter halo having a radius of 46 degrees is also sometimes visible around the Sun.

H-alpha: The photon absorbed when an electron in a hydrogen atom jumps from the second to the third energy level or the photon emitted when it jumps from the third to the second energy level.

harvest moon: The full Moon near the autumnal equinox, when it rises a short time later on a few consecutive nights.

haze: A larger than usual concentration of aerosols that produces a brighter atmosphere and diminishes the visibility of distant objects.

heliocentric hypothesis: A model in which the Sun is at the center of the solar system, with planets orbiting it.

horizon: The great circle defined by the intersection of the celestial sphere with the plane tangent to the Earth at the observer's location. It is 90 degrees away from the zenith, naturally dividing the celestial sphere into two halves: above and below. On Earth, the approximate distance of one's horizon (in miles) is equal to 1.2 times one's altitude above the surface (in feet).

hybrid eclipse: A solar eclipse that is annular near the ends but total near the middle.

ice crystals: Frozen water, which takes on a fundamentally hexagonal shape because of the structure of the water molecule, H_2O . Simple ice crystals are typically flat plates or long, thin columns, like pencils. Snowflakes tend to be larger and more complex, though still having hexagonal symmetry.

index of refraction: For any medium, the ratio of the vacuum speed of light to its speed in the medium.

infinite distance: A distance that is extremely far away compared with the size of the Earth, so that light rays coming from a point source appear to be essentially parallel.

infrared: Light that has wavelengths longer than those of visible light but shorter than those of radio waves; typically between about 10 micrometers and 1 millimeter.

interference: The property of radiation, explainable by the wave theory, in which waves in phase can add (constructive interference) and waves out of phase can subtract (destructive interference).

interstellar medium: The space between the stars, filled to some extent with gas and dust.

inverse-square law: Decreasing with the square of increasing distance. For example, the brightness of a star is proportional to the inverse-square of distance, as is the gravitational force between two objects.

ionized: Having lost at least one electron. Atoms become ionized primarily by the absorption of energetic photons and by collisions with other particles.

ionosphere: The fourth major layer of the Earth's atmosphere, typically starting at an altitude of about 60 miles. Auroras are usually formed in the ionosphere.

iridescent clouds: See **cloud iridescence**.

irradiation: An effect in which the image of a star or other point-like source of light appears larger than expected when viewed by the human eye or in a photograph; the well-focused light is scattered, spreading out and affecting neighboring regions.

isotopes: Atomic nuclei having the same number of protons but different numbers of neutrons.

isotropic: The same in all directions (that is, no preferred alignment).

Jovian planets: In our solar system: Jupiter, Saturn, Uranus, and Neptune. Planets that are large compared with Earth and consist largely of gas and liquid, with solid cores. Also called giant planets.

Kelvin: The size of 1 degree on the Kelvin (*absolute*) temperature scale, in which absolute zero is 0 K, water freezes at 273 K, and water boils at 373 K. To convert from the Kelvin scale to the Celsius (centigrade, C) scale, subtract 273 from the Kelvin-scale value. Degrees Fahrenheit (F) = $(9/5)C + 32$.

Kepler's third law: If one object orbits another, the square of its period of revolution is proportional to the cube of the semimajor axis (half of the long axis) of the elliptical orbit.

Kuiper Belt: A reservoir of perhaps millions of solar-system objects orbiting the Sun generally outside the orbit of Neptune. Eris and Pluto are the two largest known Kuiper Belt objects, though some astronomers consider them to be planets.

Large Magellanic Cloud: A dwarf companion galaxy of our Milky Way galaxy, about 170,000 light years away; best seen from Earth's southern hemisphere.

large-scale structure: The network of clusters, voids, and other shapes seen on the largest scales of the universe.

latitude: For a given point on a planet, the number of degrees north or south of the equator, with the equator being 0 degrees and the poles being 90 degrees.

lenticular cloud: A cloud with a lens-like shape, sometimes mistaken for a flying saucer.

libration: The slight apparent wobbling of the Moon, despite the synchronous rotation, so that we see more than just half of its total surface area.

light curve: A plot of an object's brightness as a function of time.

lightning: A powerful electrical discharge that generally forms from cumulonimbus clouds and is accompanied by thunder. There are many types, such as the familiar cloud-to-ground lightning, cloud-to-cloud, ribbon, sheet, bead, and others.

light year: The distance light travels through a vacuum in 1 year; about 10 trillion kilometers, or about 6 trillion miles.

Local Group: The roughly 60 galaxies, including the Milky Way, that form a small cluster.

lookback time: The duration over which light from an object has been traveling to reach us.

luminosity: Power; the total energy emitted by an object per unit of time; intrinsic brightness.

lunar eclipse: Occurs when the Moon partially and fully goes into Earth's shadow. During the penumbral phase, an observer on the Moon would see part of the Sun not blocked by Earth, but during the umbral phase, all of the photosphere is blocked (although some sunlight still bends through Earth's atmosphere and faintly illuminates the Moon).

lunar rainbow: See **moonbow**.

lunation: The total amount of time from one full Moon to the next full Moon; about 29.5 days.

magnetosphere: The magnetic field around the Earth (or another planet); parts of it may have energetic charged particles from the Sun and outer space trapped inside.

magnitude: A logarithmic measure of apparent brightness; a difference of 5 magnitudes corresponds to a brightness ratio of 100. Typical very bright stars have mag 1; typical faint naked-eye stars (in dark skies) have mag 6.

main sequence: The phase of stellar evolution, lasting about 90% of a star's life, during which the star fuses hydrogen to helium in its core.

mare: A smooth region on the Moon (or on another planet) caused by a lava flow. Plural: *maria*.

merging: The interaction of two galaxies in space, with a single galaxy as a result.

meridian: A great circle passing through the celestial poles and the zenith; the highest point in the sky reached by a star during each day-night cycle.

mesosphere: The third major layer of Earth's atmosphere, above the stratosphere, typically at altitudes of about 30 to 60 miles.

Messier catalog: A list of about 100 relatively bright star clusters, nebulae, and galaxies compiled by Charles Messier in the mid-18th century while

he was hunting for comets; different ones can be seen with the naked eye, binoculars, or a small telescope.

meteor: The streak of light in the sky (“shooting star” or “falling star”) produced when an interplanetary rock enters Earth’s atmosphere and burns up as a result of air compression. If the rock reaches Earth’s surface, it is called a *meteorite*.

meteor shower: A larger than normal rate of meteors coming from a particular direction in the sky, typically several dozen per hour. Occurs when Earth goes through the orbit of a dead or disintegrating comet.

meteor storm: An exceptionally rich meteor shower, with perhaps hundreds or even thousands of meteors per *minute* for a short time.

meteoroid: An interplanetary body smaller than an asteroid, perhaps up to a few tens of meters in diameter but typically larger than 0.1 mm.

Milky Way: The faint band of light across the sky coming from the stars and gas in the plane of the Milky Way Galaxy (our Galaxy).

mirage: An image of an object, often but not always inverted, formed by light passing through layers of air having different temperatures and densities. An *inferior mirage* forms when there is a layer of hot, low-density air below cooler, denser air. A *superior mirage* forms when there is a layer of cool, dense air below hotter, less dense air.

molecule: The smallest distinct unit of a given substance; it consists of at least two atoms. For example, the water molecule is H₂O.

Moon: Earth’s natural satellite, about 240,000 miles (60 Earth radii) away. The more generic term “moon” (not capitalized) refers to natural satellites orbiting other planets. Like planets, these moons shine by reflecting sunlight.

moonbow: A lunar rainbow, formed by sunlight reflected from the Moon.

Moon illusion: The apparently larger size of the Moon (generally gibbous or full) when it is near the horizon compared with when it is high in the sky. The effect is still not fully explained, but it may be in part a Ponzo illusion or related to the flattened appearance of the celestial sphere.

nacreous clouds: Polar stratospheric clouds that form during polar winters at altitudes of about 10 to 16 miles. They have an iridescent color that resembles mother of pearl.

nebula: A region containing an above-average density of interstellar gas and dust; often associated with either a cloud in which new stars are being born or the gas ejected from a dying star.

neutral density filter: A filter that eliminates all wavelengths of visible light by equal amounts, thereby preserving the true color of the object being observed.

neutron: Massive, uncharged particle that is normally part of an atomic nucleus.

noctilucent clouds: High-altitude clouds, typically in the mesosphere at an altitude of about 50 miles, that can reflect sunlight even in deep twilight, when the Sun is quite far below the horizon.

nuclear fusion: Reactions in which low-mass atomic nuclei combine to form a more massive nucleus.

nucleosynthesis: The creation of elements through nuclear reactions, generally nuclear fusion.

Olbers' paradox: The dark night sky; simple arguments suggest that it should be very bright.

open cluster: A loosely bound cluster of stars, usually consisting of young stars that eventually break away from the cluster.

opposition: A superior planet (that is, a planet outside Earth's orbit) is said to be in opposition when it is in the direction of the sky opposite that of the Sun. At that time, it is closer to Earth than at any other point in its orbit, and it's highest in the sky around midnight.

orbit: The trajectory of a planet going around a star, or of a planetary satellite (either natural or artificial), or of a star in a binary system, due to the mutual gravitational attraction between the two bodies.

orbital period: The time taken for an orbiting body to complete one full orbit.

ozone layer: A layer in the stratosphere, typically 12 to 25 miles above Earth's surface, that contains substantial amounts of ozone (the O₃ molecule), shielding us from much (but not all) of the Sun's ultraviolet radiation. Also, at visible wavelengths, ozone absorbs more red light than blue, leaving blue as the dominant scattered light and causing the deep blue colors of twilight far above the horizon.

parhelic circle: A faint circular band (or part of such a band) in which the sky appears slightly brighter than in neighboring regions, at the Sun's altitude above the horizon; a horizontal extension of the parhelia. Formed by sunlight being reflected mostly by the vertical sides of horizontal, plate-like ice crystals.

parhelion: Sometimes called a sundog or mock Sun; a bright, often colorful patch of light about (or slightly more than) 22 degrees from the Sun, at the Sun's altitude above the horizon. Parhelia can form on either side of the Sun when light passes through roughly horizontal, plate-like, hexagonal ice crystals.

Parry arc: A faint patch of light that is sometimes seen just above the upper tangent arc; formed by sunlight going through hexagonal ice crystals.

partial eclipse: When only part of the Moon is in the Earth's umbral shadow or when only part of the Sun is blocked by the Moon.

penumbra: The partial shadow of an object, from within which it appears that the Sun is not fully blocked.

perigee: For an orbit around the Earth, the point of closest approach to the Earth.

period: The time taken for an orbiting body to complete one full orbit. Also, the inverse of the frequency of a wave or oscillating body.

phase: In the case of the Moon or a planet seen from Earth, the degree to which the visible hemisphere appears illuminated; the sequence of phases is new, waxing crescent, first quarter, waxing gibbous, full, waning gibbous, third quarter, waning crescent, and back to new. Also, the physical state of a substance: gaseous, liquid, or solid.

phase transition: The transformation of matter from one phase (e.g., liquid) to another (e.g., solid).

photon: A quantum, or package, of electromagnetic radiation that travels at the speed of light. From highest to lowest energies: gamma rays, X-rays, ultraviolet, optical (visible), infrared, and radio.

photosphere: The visible surface of the Sun (or another star) from which light escapes into space.

pinhole camera: A hole in an opaque sheet used to project an image of the Sun.

planet: A body that primarily orbits a star (so that moons don't count), is large enough to be roughly spherical (typically, larger than about 600 km in diameter), gravitationally dominates its region of space (that is, has largely cleared away other debris), and has never undergone nuclear fusion.

planetary system: A collection of planets and smaller bodies orbiting a star (e.g., our solar system).

planetary transit: The passage of a planet directly along a star's line of sight, causing a temporary dimming of the star's light; can be used to detect planets in other planetary systems.

planisphere: A simple device that shows the stars and constellations that are visible from a given latitude or range of latitudes as a function of month and time of night.

plasma: Ionized gas; sometimes called a fourth state of matter.

polarized light: Polarized light has an excess of waves whose electric field is oscillating in a particular direction, whereas unpolarized light has no preferred plane of oscillation. A polarizing filter passes only a particular plane of polarization. Reflection, or scattering, also tends to polarize light.

poles: On a planet, the points at which the rotation axis intersects the surface.

pole star: A star approximately at a celestial pole (currently Polaris, in the north).

Ponzo illusion: When two objects of equal physical size are placed near or on apparently converging parallel lines, the one that is closer to the convergence point appears larger.

positive streamer: A path of ionized air generally having a positive charge that starts to form near the ground, often at a high point, making its way upward and eventually joining with the stepped leader.

prograde motion: The apparent motion of the planets when they appear to gradually move from west to east among the stars; *retrograde motion* is the opposite direction.

prominences: Hot plumes of gas streaming from the Sun's photosphere along the lines of the Sun's magnetic fields.

proton: Massive, positively charged particle that is normally part of an atomic nucleus. The number of protons in the nucleus determines the chemical element.

protoplanetary disks: Also called *proplyds*; concentrations of matter around newly formed or still forming stars out of which planets may form.

protostar: A star still in the process of forming in a cloud of gas and dust, collapsing nearly in free fall.

purple light: A diffuse purple glow that is sometimes visible above the twilight arch. Produced by a combination of blue light Rayleigh-scattered by relatively low parts of the atmosphere and scattering by dust particles in the stratosphere. Tends to occur most frequently after volcanic eruptions.

radial velocity: The speed of an object along the line of sight to the observer.

radiant: The point or region in the sky from which the meteors in a given meteor shower appear to come.

rainbow: The spectrum of sunlight produced by the dispersion of light passing through raindrops. The primary rainbow is the inner one; its colors go from violet on the inside (at an angle of 40 degrees from the antisolar point) to red on the outside (at an angle of 42 degrees from the antisolar point). The outer, secondary rainbow has reversed colors ranging from about 51 to 54 degrees.

raindrops: Generally spherical drops of water falling to the ground from clouds; most of them are between 0.1 and 5 millimeters in diameter, though those forming rainbows are typically 1–2 millimeters in size.

recombination: Process by which electrons combine with protons and other atomic nuclei to form neutral atoms; believed to have first occurred about 380,000 years after the Big Bang.

red giant: The evolutionary phase following the main sequence of a relatively low-mass star, such as the Sun; the star grows in size and luminosity but has a cooler surface.

reflected rainbow: A rainbow that appears as a reflection in the surface of a body of water roughly opposite the Sun. It is not the reflection of the primary bow visible above ground but, rather, of another more distant rainbow that is not directly seen.

reflecting telescope: Telescope that uses a mirror instead of a lens to collect light; unlike the refracting telescope, it brings all colors into focus together.

reflection: The “bouncing” of a light wave off of a surface, so that it changes direction. In all cases, the reflected wave makes the same angle as the incident wave, relative to a line perpendicular to the reflecting surface.

reflection rainbow: A rainbow in the sky formed after sunlight reflects off the surface of a body of water that is behind the observer, in the Sun’s general direction. It appears roughly opposite the Sun, just outside the normal primary rainbow, merging with the primary bow near the ground.

refracting telescope: Telescope that uses a lens to collect light and bring it to a focus.

refraction: The bending of light as it passes from one medium to another having different properties. The speed of light in the medium is equal to the vacuum speed divided by the index of refraction.

relativistic: Having a speed that is such a large fraction of the speed of light that the special theory of relativity must be applied.

resolution: The clarity of detail produced by a given optical system (such as a telescope).

rest wavelength: The wavelength radiation would have if its emitter were not moving with respect to the observer.

retrograde motion: The apparent backward (east-to-west) motion among the stars that planets undergo for a short time each year.

return stroke: The return current from the ground to the cloud after the downward motion of the stepped leader, generally forming the main bolt of a lightning flash.

satellite: An object orbiting another body; for example, the Moon is Earth's natural satellite. Artificial satellites are generally in three main classes: low-Earth orbit (within a few hundred miles), middle-Earth orbit (a few Earth radii), and high-Earth orbit (typically geostationary, at 5.5 Earth radii from Earth's surface).

scattering: The bouncing, or reflection, of light by particles in the beam. Particles much smaller than the wavelength of light tend to scatter short wavelengths much more efficiently than long wavelengths; a good example is Rayleigh scattering of sunlight by air molecules, which is inversely proportional to the fourth power of wavelength, making the sky blue and the setting (or rising) Sun reddish orange.

seasons: Winter, spring, summer, and fall (or autumn). Caused by the fact that Earth's axis of rotation is tilted by 23.5 degrees relative to its axis of revolution around the Sun, making the Sun's path higher in the sky during summer and lower in the sky during winter.

shade 14 welder's glass: A filter that can be safely used to view the uneclipsed or partially eclipsed Sun; it cuts out about 99.999% of the light, including infrared and ultraviolet.

shadow bands: Subtle dark and light ripples shimmering along the ground for a few minutes before or after totality during a solar eclipse. Caused by the twinkling of the thin crescent Sun.

solar activity cycle: The cycle over which solar activity varies, as measured by the number of sunspots, prominences, solar flares, and coronal mass ejections; the period is typically about 11 years.

solar eclipse: A full or partial covering of the Sun's photosphere (visible surface) when the Moon is between the Earth and the Sun. The partial phases must be viewed through a protective filter or by projection techniques, such as a pinhole camera.

solar filter: A filter that cuts out about 99.999% of all light regardless of wavelength, allowing one to safely view the uneclipsed or partially eclipsed Sun. Also, a filter that transmits only a narrow range of specific wavelengths, such as an H α filter useful for viewing solar prominences.

solar flare: An explosive release of energy from a relatively small portion of the Sun's surface; marked by extremely high temperatures and very high-speed particles.

solar system: The Sun and its orbiting bodies: the planets (Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, Neptune), dwarf planets (such as Pluto and Ceres), asteroids (most of which orbit between Mars and Jupiter), Kuiper Belt objects (icy objects generally past the orbit of Neptune), and comets (which originate in the Kuiper Belt and the Oort Cloud).

solar wind: A continuous stream of charged particles heading outward from the Sun's corona; can vary with time owing to prominences, solar flares, and coronal mass ejections.

solstice: The northernmost or southernmost point on the celestial sphere that the Sun reaches or the time of the year when the Sun reaches this point.

space weather: The effects caused when charged particles from the Sun interact with Earth's magnetic field and atmosphere.

special theory of relativity: Einstein's 1905 theory of relative motion, gravity excluded.

spectrum: A plot of the brightness of electromagnetic radiation from an object as a function of wavelength or frequency.

spiral galaxy: One of the two major classes of galaxies defined by Edwin Hubble; made up of a roughly spherical central “bulge” containing older stars, surrounded by a thin disk in which spiral arms are present.

sporadic meteor: A meteor that is not associated with a known meteor shower.

sprite: A flash of light lasting a few milliseconds, high in the upper atmosphere (mesosphere) above rare positive lightning discharges in thunderstorms. It is an electrical discharge in cold ionized gases.

star: A distant sun. A large, gravitationally bound sphere of gas that is undergoing (or used to undergo) nuclear reactions in its hot core.

star chart: A map of the sky showing the positions of stars and other objects, such as star clusters, nebulae, and galaxies. The boundaries of constellations are often marked. Also called a star atlas, especially if more details are shown.

star cluster: A gravitationally bound group of stars that formed from the same nebula; the two main types are open and globular.

star party: An informal name often given to a public star-viewing session organized by a local amateur astronomy club or planetarium.

St. Elmo’s fire: A faint, bluish-violet glow that can surround tall, pointy objects, such as lightning rods and spires, during thunderstorms.

stepped leader: A path of ionized air generally having a negative charge that starts to form near the bottom of a cloud, making its way downward toward the ground in a series of discrete jumps.

stratosphere: The second major level of Earth’s atmosphere, above the troposphere; it is typically about 8 to 30 miles above sea level.

subsun: A sun pillar below the Sun in the sky, best visible shortly before sunset or shortly after sunrise. Formed by sunlight reflecting off horizontal, plate-like ice crystals.

Sun: The star around which Earth orbits.

sundog: See **parhelion**.

Sun-grazing comet: A comet that comes very close to the Sun and, in some cases, plunges into the Sun.

sun pillar: A faint pillar of light above the Sun in the sky, best visible after sunset; formed by sunlight reflecting off horizontal, plate-like ice crystals. It can also appear below the Sun, in which case it is often called a subsun.

sunspots: Cooler regions on the Sun's photosphere that appear as dark blotches on the photosphere. They have strong, tangled magnetic fields that block hotter plasma rising from the Sun's interior.

supercooled: The condition in which a substance is cooled below the point at which it would normally make a phase change, such as from liquid to solid.

supergiant: The evolutionary phase following the main sequence of a massive star; the star becomes more luminous and larger. If its size increases by a very large factor, it becomes cool (red).

supernova: The violent explosion of a star at the end of its life.

supernova remnant: The cloud of chemically enriched gases ejected into space by a supernova.

supernumerary bows: The faint light and dark bands bordering the inside edge of the primary rainbow, produced by constructive and destructive interference.

synchronous rotation: The rotation of a body having the same period as its orbit.

tangent: A straight line that just barely touches another curved line or surface; the single point of intersection is called the “tangent point.”

tangent arc: A faint arc of light tangent to and outside the 22-degree halo; called the upper tangent arc if above the Sun and the lower tangent arc if below it. Formed by sunlight passing through long, thin ice crystals that are roughly horizontal.

telescope: A device that collects light from distant objects, making them brighter and easier to see; the image is also magnified.

terminator: The boundary between night and day on a moon or planet; the edge of the part that is lighted by the Sun.

terrestrial planets: Rocky, Earth-like planets. In our solar system: Mercury, Venus, Earth, and Mars.

thunder: The sound that is formed by lightning when superheated air expands supersonically, sending a shock wave through the atmosphere.

tidal force: The difference between the gravitational force exerted by one body on the near and far sides of another body.

totality: The stage of a total solar eclipse when all of the Sun’s photosphere is blocked by the Moon.

transit: A transit occurs when a planet passes directly between Earth and either the Sun or another star. Also, a star is said to “transit” when it reaches its highest point in the sky, as seen from Earth’s surface.

troposphere: The lowest level of Earth’s atmosphere, where almost all clouds and weather-related phenomena are located. Its thickness varies with latitude but is typically about 8 miles. The temperature generally decreases with increasing height in the troposphere.

twilight: The time after sunset (or before sunrise) when the sky is not fully dark. During civil, nautical, and astronomical twilight, the Sun is (respectively) 0 to 6 degrees, 6 to 12 degrees, and 12 to 18 degrees below the horizon.

twilight arch: A bright, colorful glow in the western sky near or shortly after sunset or in the eastern sky near or shortly before sunrise.

twinkling: Rapid changes in the apparent brightness of a star; caused by light passing through turbulent layers in Earth's atmosphere having different densities and temperatures.

UFO: Unidentified flying object. In principle, any object in the sky whose nature is not identified by the viewer, though conventionally, the term is restricted to mean a spacecraft from an alien planet. There is currently no compelling evidence for the existence of genuine UFOs.

ultraviolet: Light that has wavelengths shorter than those of visible light but longer than those of gamma rays and X-rays; typically between about 10 and 400 nanometers.

umbra: The dark part of the shadow of an object, from within which it appears that the Sun is fully blocked.

universe: All that there is within the space and time dimensions accessible to us, as well as regions beyond (but still physically connected to) those that we can see.

Van Allen belts: Regions in Earth's magnetosphere where there is a concentration of charged particles from the Sun and outer space.

vanishing point: The distant point at which parallel lines appear to converge due to perspective.

variable star: A star whose apparent brightness changes with time.

virga: Precipitation that evaporates before reaching the ground.

waning: Getting progressively smaller; specifically, the Moon is waning from full Moon to new Moon.

wavelength: The distance over which a wave goes through a complete oscillation; the distance between two consecutive crests or two consecutive troughs.

waxing: Getting progressively larger; specifically, the Moon is waxing from new Moon to full Moon.

white light: Sunlight or any other light whose spectrum contains all the colors of the rainbow with roughly the same proportions as in sunlight.

wormhole: A hypothetical connection between two universes or different parts of our universe. Also, *Einstein-Rosen bridge*.

year: The Earth's orbital period around the Sun.

zenith: The point on the celestial sphere that is directly above the observer.

zodiac: The band of constellations through which the Sun moves during the course of a year. There are 12 classical zodiacal constellations; however, taking into account the formal constellation boundaries, Ophiuchus could be considered the 13th zodiacal constellation.

zodiacal light: A faint glow in the night sky around the ecliptic, stretching up from the western horizon shortly after evening twilight and up from the eastern horizon shortly before morning twilight; it is produced by sunlight reflected from interplanetary dust. If the light is seen far from the direction of the Sun, it is sometimes called the zodiacal band.

Bibliography

Chandler, David S. *The Night Sky Planisphere*. Springville, CA: The David Chandler Company, 1992. An excellent planisphere that shows you which constellations are visible at different times of the night and year. There are different versions, depending on your latitude.

Dickinson, Terence. *Nightwatch: A Practical Guide to Viewing the Universe*, 4th ed. Buffalo, NY: Firefly Books, 2006. An excellent beginner's guide to observing the night sky, for viewers in the Northern Hemisphere. Topics also include lunar and solar eclipses, observation of the Sun, equipment, photography tips, and more.

Edmund Scientific. *Edmund Mag 5 Star Atlas*. Barrington, NJ: Edmund Scientific, 1989. A set of very nice star maps showing stars as faint as fifth magnitude, roughly what you can see from a relatively dark site (but not the darkest sites). This approach is useful because some of the other star atlases show too many stars, in a sense, making it harder to see the patterns made by the brighter stars.

Espenak, Fred. *Fifty Year Canon of Solar Eclipses*. Cambridge, MA: Sky Publishing, 1987. A thorough listing of solar eclipses, their locations, durations, and other facts.

Ferris, Timothy. *Coming of Age in the Milky Way*. New York: Harper Perennial, 2003. An excellent discussion of our Milky Way galaxy.

Gleick, James. *Isaac Newton*. London: Vintage, 2004. Interesting and authoritative account of the life and scientific work of perhaps the greatest physicist (along with Einstein) ever to have lived.

Golub, Leon, and Jay M. Pasachoff. *Nearest Star: The Surprising Science of Our Sun*. Cambridge, MA: Harvard University Press, 2002. Contains much information about our Sun and solar activity.

Hamblyn, Richard. *The Cloud Book: How to Understand the Skies*. Cincinnati, OH: David & Charles, 2008. Includes helpful color photographs and discussions of the different types of clouds, organized by altitude and type into 27 categories, an approach introduced by the World Meteorological Organization (1937) that places more emphasis on how clouds grow, turn into one another, and decay. Briefer attention is also given to optical phenomena, such as coronas, halos, parhelia, sun pillars, the circumzenithal arc, the glory, and crepuscular rays.

Harris, Joel, and Richard Talcott. *Chasing the Shadow: An Observer's Guide to Solar Eclipses*. Waukesha, WI: Kalmbach Publishing Co., 1994. An excellent guide to observing partial and total solar eclipses safely and thoroughly.

Harrison, Edward. *Darkness at Night: A Riddle of the Universe*. Cambridge, MA: Harvard University Press, 1989. Contains an excellent discussion of Olbers' paradox, concerning the darkness of the night sky.

Hoeppe, Götz. *Why the Sky Is Blue: Discovering the Color of Life*. Translated by John Stewart. Princeton, NJ: Princeton University Press, 2007. A somewhat technical but clear discussion of the blue sky; includes the role of ozone in the production of the blue twilight sky.

Kitchen, Chris, and Robert W. Forrest. *Seeing Stars: The Night Sky through Small Telescopes*. Berlin/New York: Springer, 1997. A fine introduction to viewing celestial objects through a small telescope.

Levy, David H. *David Levy's Guide to the Night Sky*. Cambridge: Cambridge University Press, 2001. An excellent, extensive guide to observing the night sky with the naked eye and inexpensive equipment; most suitable for beginners who want to become serious amateur astronomers. Includes a detailed discussion of the various features visible on the Moon at different lunar phases and provides advice regarding equipment, such as binoculars and telescopes.

Lewin, Walter. *For the Love of Physics*. New York: Free Press, 2011. Has an excellent discussion of rainbows, with some material on lightning, as well. Also contains a great deal of other fascinating material from a world-renowned teacher at MIT.

Littmann, Mark, Ken Willcox, and Fred Espenak. *Totality: Eclipses of the Sun*. New York: Oxford University Press, 1999. An excellent introduction to solar eclipses and how to view them.

Long, Kim. *The Moon Book: Fascinating Facts about the Magnificent, Mysterious Moon*. Boulder, CO: Johnson Books, 1998. All about the Moon and various phenomena associated with it.

Lynch, David K., and William Livingston. *Color and Light in Nature*, 2nd ed. Cambridge: Cambridge University Press, 2001. A wonderful book that explains all kinds of atmospheric phenomena, such as rainbows, halos, coronas, and arcs, written by two people who have spent much time observing them.

MacLachlan, James. *Galileo Galilei: First Physicist*. New York: Oxford University Press, 1999. Describes the life and scientific contributions of Galileo Galilei, one of the greatest astronomers and physicists of all time.

Maor, Eli. *Venus in Transit*. Princeton, NJ: Princeton University Press, 2004. Discusses the rare transits of Venus across the disk of the Sun.

Marschall, Laurence A. *The Supernova Story*. Princeton, NJ: Princeton University Press, 1994. Discusses the discovery and study of Supernova 1987A, the brightest supernova in nearly four centuries.

Minnaert, Marcel G. J. *Light and Color in the Outdoors*. Translated by L. Seymour. Berlin/New York: Springer, 1995. A classic book on various atmospheric phenomena produced by the interaction of sunlight with water drops and ice crystals. Goes into a fair amount of the physics and mathematics, but those sections can be skipped if the reader isn't interested.

Naylor, John. *Out of the Blue: A 24-Hour Skywatcher's Guide*. Cambridge: Cambridge University Press, 2002. Excellent, well-written discussion of various atmospheric phenomena produced by the interaction of sunlight with air, water drops, and ice crystals. Also a very good introduction to night sky phenomena, eclipses, the Moon, planets, comets, meteors, satellites, auroras, and other topics relevant to this course.

Pasachoff, Jay M. *A Field Guide to Stars and Planets*, 4th ed. Boston: Houghton Mifflin, 1999. Good reference book for the stars and planets, their basic properties, and how to observe them.

Pasachoff, Jay M., and Alex Filippenko. *The Cosmos: Astronomy in the New Millennium*, 3rd ed. Belmont, CA: Thomson Brooks/Cole, 2007. Award-winning textbook on introductory astronomy; includes planets, stars, clusters, nebulae, galaxies, and the universe as a whole. Thorough summaries and extensive sets of review questions.

Rey, H. A. *Find the Constellations*, 2nd ed. Boston: Houghton Mifflin Harcourt, 2008. An excellent guide to finding and recognizing the constellations, by the author of the *Curious George* series. Much of the material is the same as in *The Stars: A New Way to See Them*, somewhat simplified. Though nominally intended for readers aged 9 to 12, the book is suitable for all beginning observers of stars and constellations.

———. *The Stars: A New Way to See Them*, 2nd ed. Boston: Houghton Mifflin Harcourt, 2008. A great book about the planets, stars, and constellations, written by the author of the *Curious George* series. First published in 1952, it has been updated and revised, and the latest version (2008) even discusses the reclassification of Pluto as a “dwarf planet.” Suitable for all beginning observers of stars and planets.

Ridpath, Ian. *Norton's Star Atlas*, 20th ed. New York: Dutton, 2003. An outstanding resource that contains detailed star charts and a large amount of information on observing the night sky, with and without binoculars or telescopes. A classic that has been regularly updated. Includes detailed maps of the Moon, explanations of celestial coordinates, and a wealth of other useful information.

Ruhl, Antonin, and Gary Seronik. *Atlas of the Moon*, rev. ed. Cambridge, MA: Sky Publishing, 2007. A detailed atlas showing lunar features that can be observed with the naked eye, binoculars, and telescopes.

Tirion, Wil. *The Cambridge Star Atlas*, 3rd ed. Cambridge: Cambridge University Press, 2001. An extremely thorough and accurate star atlas that also shows the locations of deep-sky objects, such as star clusters, galaxies, and nebulae.

World Meteorological Organization. *International Cloud Atlas*. Geneva: World Meteorological Organization, 1975 (vol. 1) and 1987 (vol. 2). Difficult to find, and only the second volume is potentially interesting for general users: It's an authoritative collection of several hundred full-page photographic plates. Earlier editions also appeared in a one-volume abridged version, with substantially fewer photographs but retaining much of the textual material.

Websites

Astronomy. <http://www.astronomy.com>: The home page of *Astronomy* magazine (Waukesha, WI: Kalmbach Publishing). An excellent monthly guide to what is observable in the night sky, positions of planets, articles on new discoveries in astronomy, and reviews of telescopes and other equipment. You can subscribe to the monthly magazine and some of the Internet features; others are free.

Astronomy Café. <http://www.astronomycafe.net>: Answers to questions about astronomy.

Atmospheric Optics. <http://www.atoptics.co.uk>: An excellent site that explains (and shows photographs of) various atmospheric phenomena, such as sundogs, coronas, and halos. The “picture of the day” is posted at <http://www.atoptics.co.uk/opod.htm>.

Cloud Appreciation Society. <http://cloudappreciationsociety.org/>: A society for lovers of clouds and atmospheric phenomena. For example, check out the beautiful cloud photo gallery to find all kinds of clouds.

Clouds-online.com. <http://www.clouds-online.com/>: An abridged, English-language version of a more extensive German website, <http://wolken-online.de>. Shows many photographs of all the different cloud varieties.

Google Sky. <http://www.google.com/sky/>: A great Internet resource that allows you to view the celestial sphere; you can zoom in on different regions and objects, learning interesting information about them.

Green Flash. <http://mintaka.sdsu.edu/GF/>: A useful resource on the green flash; provides photographs, explanations, animations, viewing hints, and so on.

Heavens-Above. <http://www.heavens-above.com>: This site allows you to determine which artificial satellites will be visible from your location (and at what times and positions in the sky). Also provides other useful information, such as lunar phase, times of twilight, and so on.

Meteor Showers Online. <http://meteorshowersonline.com/>: A good listing of meteor showers and tips on how to observe them.

MrEclipse.com. <http://www.MrEclipse.com/>: An excellent website containing information on future solar and lunar eclipses, safe viewing, photography, and related topics.

NASA. <http://www.nasa.gov>: The official NASA website; contains updates on various NASA space missions and information on when and where to see the International Space Station. Also provides many links.

NASA Astronomy Picture of the Day. <http://antwrp.gsfc.nasa.gov>: A wonderful site that shows a different astronomical image each day, along with an explanatory paragraph containing links to additional information.

NASA Eclipse Webpage. <http://eclipse.gsfc.nasa.gov>: The website to visit if you are interested in seeing a lunar or solar eclipse or a planetary transit. For each eclipse, the site provides a large amount of useful information on the eclipse path, viewing times, weather predictions, and so on.

NASA Hubble Space Telescope. <http://hubblesite.org/newscenter/>: Photographs and press releases from the Hubble Space Telescope.

NASA Solar and Heliospheric Observatory. <http://sohowww.nascom.nasa.gov/>: One of several excellent websites on solar activity, sunspots, coronal mass ejections, Sun-grazing comets, and similar phenomena.

NOAA Photo Library. <http://www.photolib.noaa.gov/>: The public photo library of the National Oceanic and Atmospheric Administration; an excellent resource.

Polar Image. <http://www.polarimage.fi>: Pekka Parviainen, who lives in Finland, has taken many thousands of beautiful photographs of clouds, rainbows, halos, meteors, and other phenomena in the day and night skies.

Sky & Telescope. <http://www.skyandtelescope.com>: The home page of *Sky & Telescope* magazine (Sky Publishing, a New Track Media Company). An excellent monthly guide to what's observable in the night sky, positions of planets, articles on new discoveries in astronomy, and reviews of telescopes and other equipment. You can subscribe to the monthly magazine and some of the Internet features; others are free. Slightly more technical than *Astronomy* magazine.

Skymaps.com. <http://www.skymaps.com>: Provides good, printable night-sky maps for each month, along with a description of upcoming celestial events; useful for both hemispheres.

SpaceWeather.com. <http://www.spaceweather.com>: An excellent site about the continually changing sky. Includes information on solar activity, auroras, meteor showers, and other celestial events.

Star of the Week. <http://stars.astro.illinois.edu/sow/sowlist.html>: Gives interesting information about the individual bright stars visible in the night sky.

WeatherVideoHD.TV. <http://www.weathervideohd.tv/>: An excellent Web site showing photographs and videos of storms, lightning, clouds, atmospheric effects, and so on.

Weatherwise. <http://www.weatherwise.org/>: The home page of *Weatherwise* magazine (Philadelphia, PA: Taylor & Francis). Lots of nontechnical, interesting information about the weather. You can subscribe to the bimonthly magazine and some of the Internet features; others are free.

Weather World 2010 Project. <http://ww2010.atmos.uiuc.edu/%28Gh%29/home.rxml>: An excellent set of photographs, explanations, and diagrams of various weather-related topics and atmospheric phenomena, including rainbows and halos.

WorldWide Telescope. <http://www.worldwidetelescope.org/Home.aspx>: A great Internet resource that allows you to learn about objects in the sky and see images obtained with different kinds of telescopes. Also includes guided tours of the sky.